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Future sustainable water desalination technologies for the Saudi Arabia: A review

A.M.K. El-Ghonemy *

Engineering college, Al-Jouf University, KSA, Saudi Arabia

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ABSTRACT

Water and energy are two of the most important topics on the international environment and development agenda. The social and economic health of the modern world depends on sustainable supply of both energy and water. Many areas worldwide that suffer from fresh water shortage are increasingly dependent on desalination as a highly reliable and non-conventional source of fresh water. So, sea water desalination market has greatly expanded in recent decades and expected to continue in the coming years.

Water supply in Saudi Arabia relies mainly on desalination. Saudi Arabia has the largest desalination market in the world. In KSA the average annual direct normal irradiance (DNI) is more than 6 kWh/m^2/day, which are preferred for concentrated solar power (CSP) operation.

This paper provides a comprehensive review of desalination technologies that are sustainable for future applications in Saudi Arabia (KSA). More focus was directed to the poly-generation of energy and water by means of solar energy, with emphasis on technologies economics and environmental impacts. The study also includes existing and future desalination projects that have been applied in KSA. A comparative study between different renewable energy technologies powered desalination systems as well as performance and economics have been done. Finally, some general guidelines are given for the selection of desalination and renewable energy systems and the parameters that are need to be considered.

* Tel.: +966 595188023.
E-mail address: amghonemy@yahoo.com

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Nomenclature

Bm^3/y	one billion cubic meter per year
CSP	concentrating solar thermal power stations
D	density
DC	direct current
DNI	direct normal irradiance (solar beam radiation on ideal sun-tracking collectors)
EPA	Environmental Protection Agency
EU	Europe
F	fuel
Fresnel	inventor of a facetted concentrating mirror assembly
GWI	Global Water Intelligence
HTF	high temperature fluid
Hybrid	mixture of solar and fossil primary energy in a concentrating solar power plant
ISC	short circuit current
KSA	Kingdom of Saudi Arabia
kVAR	kilo volt ampere reactive
kWh	kilo watt hour
LCC	life cycle cost
LC	lethal concentration
Med	mediterranean region
MED	multi-effect-desalination
MENA	Middle East & North Africa
Mm^3	million cubic meters
MSF	multi-stage-flash desalination
MVC	mechanical vapor compression
MPPT	maximum power point
O&M	operation and maintenance
PNEC	predicted no effect concentration
ppm	parts per million (milligram per liter)
PV	photovoltaic
(PV-RO)	photovoltaic-powered reverse osmosis system
S	salinity
T	temperature
TVC	thermal vapor compression
UHCPV	ultra high concentration photovoltaic

Greek symbols

η	efficiency

Subscripts

el	electric

1. Introduction

1.1. Natural water resources

Water is one of the most abundant resources on earth, covering three fourths of the planet's surface. About 97% of the earth's water is salt water in the oceans and 3% is fresh water contained in the poles (in the form of ice), ground water, lakes and rivers, which supply most of human and animal needs. Nearly 70% from this tiny 3% of the world's fresh water is frozen in glaciers, permanent snow cover, ice and permafrost. The other thirty percent of all fresh water is underground, most of it in deep, hard-to-reach aquifers. Lakes and rivers together contain just a little more than 0.25% of all fresh water; lakes contain most of it [1–3]. Fig. 1 illustrates the water distribution on the earth.

1.2. Water demand and consumption

Man has been dependent on rivers, lakes and underground water reservoirs for fresh water requirements in domestic life, agriculture and industry. About 70% of total water consumption is used by agriculture, 20% is used by the industry and only 10% of the water consumed worldwide is used for household needs [1]. However, rapid industrial growth and the worldwide population explosion have resulted in a large escalation of demand for fresh water, both for the household needs and for crops to produce adequate quantities of food. Added to this is the problem of pollution of rivers and lakes by industrial wastes and the large amounts of sewage discharged. In total, water demand doubles every 20-year, so the water emergency situation is certainly very alarming [2,3].

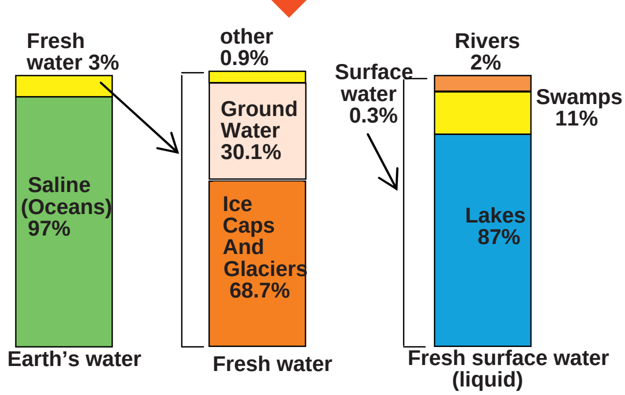

Fig. 1. Water distribution on the earth [1–3].

1.3. The need for desalination

Desalination in general means to remove salt from saline water. According to World Health Organization (WHO), the permissible limit of salinity in water is 500 ppm (ppm) and for special cases up to 1000 ppm, while most of the water available on earth has salinity up to 10,000 ppm, and seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts [1–3].

Excess water salinity causes the problem of taste, stomach problems and laxative effects. The purpose of a desalination system is to clean or purify brackish water or seawater and supply water with total dissolved solids within the permissible limit of 500 ppm or less. This is accomplished by several desalination methods that will be mentioned below.

1.4. Desalination and energy

In general, energy is as important as water for the development of good standards of life because it is the force that puts all human activities in operation. Desalination processes require significant quantities of energy to achieve separation of salts from seawater. The dramatic increase of desalinated water supply will create a series of problems, the most significant of which are those related to energy consumption and environmental pollution caused by the use of fossil fuels. Renewable energy systems produce energy from sources that are freely available in nature.

Their main characteristic is that they are friendly to the environment, i.e. they do not produce harmful effluents. Production of fresh water using desalination technologies driven by renewable energy systems is thought to be a viable solution to the water scarcity at remote areas characterized by lack of potable water and conventional energy sources like heat and electricity grid. Worldwide, several renewable energy desalination pilot plants have been installed and the majority has been successfully operated for a number of years. Virtually, all of them are custom designed for specific locations and utilize solar, wind or geothermal energy to produce fresh water. Operational data and experience from these plants can be utilized to achieve higher reliability and cost minimization. Although renewable energy powered desalination systems cannot compete with conventional systems in terms of the cost of water produced, they are applicable in certain areas and are likely to become more widely feasible solutions in the near future.

1.5. Overview of desalination market

1.5.1. Global installed desalination capacity by process

The globally installed desalting capacity by process is shown in Fig. 2. From this chart, it is clear that Reverse Osmosis (RO) and multistage flash (MSF) account for 53% and 34% of total installed desalination capacities respectively. Though both thermal process (MSF & MED) and membrane separation process are used worldwide but now trend is shifting towards membrane separation process [4].

1.5.2. Global installed desalination capacity by feed-water sources

Sea water desalination is being applied at 58% of installed capacity worldwide, followed by brackish water desalination accounting for 23% of installed capacity [1,2]. Fig. 3 outlines the global desalting capacity ranked according to feed water sources.

1.5.3. Global installed desalination capacity by country

The top five countries where maximum desalination capacity is located are sown in Table 1. It is clear that, the maximum desalination capacity is in Saudi Arabia followed by USA [5].

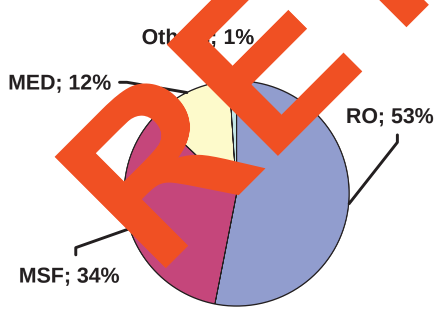

Fig. 2. Global installed desalting capacity by process [4,5].

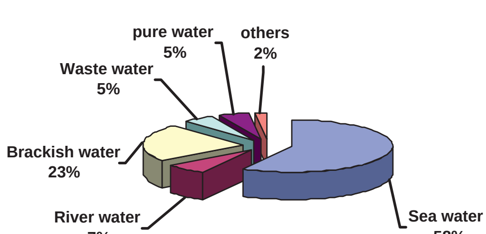

Fig. 3. Global installed desalination capacity by feed-water sources [4,5].

Table 1
The top five countries in desalination capacities [5].

Country	Total Capacity (m^3/day)	% of Global production	MSF	MED	MVC	RO	ED
Saudi Arabia	5,253,200	25.9	67.7	0.3	1.2	31	1.9
United State	3,092,500	15.2	1.7	1.8	4.5	78	11.4
United Arab Emirates	2,164,500	10.7	10.7	0.4	3.0	6.5	0.2
Kuwait	1,538,400	7.6	7.6	0.7	0.0	3.4	0.3
Japan	745,300	3.6	3.7	2.0	0.0	86.4	6.8

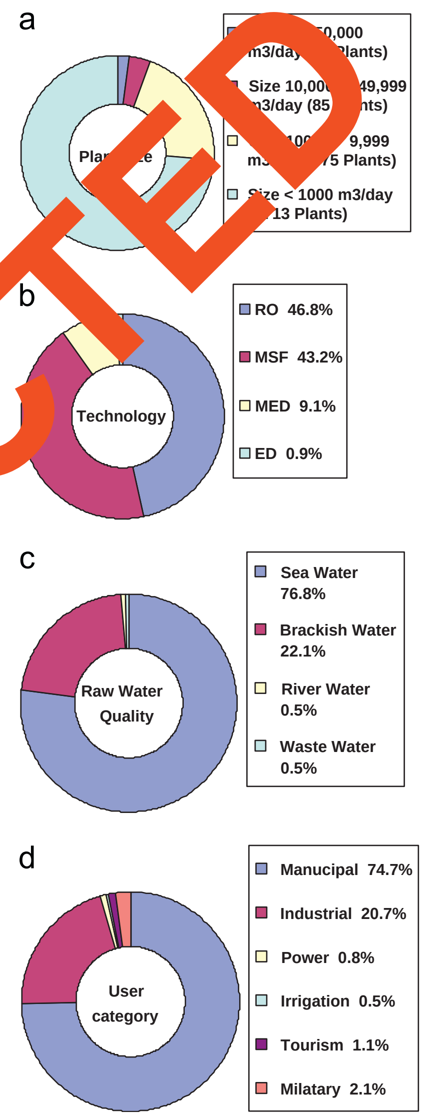

Fig. 4. KSA installed capacity by plant size, technology, raw water quality and user category [4,5].

From Table 1 it is clear that, Kingdom of Saudi Arabia (KSA) has the largest market in the world (60%). Up to year 2010, detailed description for KSA water desalination plants was listed and tabulated as shown in Appendix A2 [4,5]. Based on these data, the following analysis are made for KSA installed capacity by plant size, technology, raw water quality and user category, as indicted in Fig. 4a, b, c, and d respectively [4,5].

1.6. Objectives

This paper provides a comprehensive review of sustainable desalination technologies that are applicable in Saudi Arabia (KSA). More focus was directed to the poly-generation of energy and water by means of solar energy using concentrated solar power (CSP) systems, with emphasis on technologies, economics and environmental impacts. The study also includes existing and outlook desalination projects that have been applied in KSA. A comparative study between different renewable energy technologies powered desalination systems as well as performance and economics have been done. Finally, some general guidelines are given for selection of desalination and renewable energy systems and the parameters that are need to be considered.

2. Desalination technologies

There is a large number of different desalination technologies available and applied worldwide. Some of them are fully developed and applied on a large scale, while others are still used in small units for demonstration purposes or for research and development. Table 2 gives a selection of the most commonly applied technologies.

Commercial desalination technologies can be classified mainly based on the desalination processes either thermal desalination using distillation such as multi-stage flash (MSF) and multi-effect distillation (MED) or membrane based desalination such as reverse osmosis (RO) technology. The thermal desalination methods are that evaporate seawater by using heat from combustion or from the cold end of a power plant. In the other hand, mechanical methods are that use filtration through membranes. While, vapor compression technologies are mainly used in combination with thermal distillation in order to increase volumes and efficiency of those processes.

Table 2
Overview of contemporary desalination methods [6].

Separation	Energy use	Process	Desalination method
Water from salts	Thermal	Evaporation	Multi-stage flash (MSF) Multi-effect distillation (MED) Thermal vapor compression (TVC) Solar distillation (SD)*
		Crystallization	Freezing (FR) Gas hydrate processes (GH)
		Filtration/Evaporation	Membrane distillation (MD)
	Mechanical	Evaporation	Mechanical Vapor compression (MVC)
		Filtration	Reverse osmosis (RO)
Salts from water	Electrical	Selective filtration	Electrodialysis (ED)
	Chemical	Exchange	Ion exchange (IE)

2.1. Multi-stage flash desalination (MSF)

MSF is a thermal distillation process that involves evaporation and condensation of water. The evaporation and condensation steps are coupled to each other in several stages so that the latent heat of evaporation is recovered for reuse by preheating incoming water as shown in Fig. 5. In the so called brine heater, the incoming feed water is heated to its maximum temperature (top brine temperature) by condensing saturated steam from the cold end of a steam cycle power plant or from another heat source as shown in Fig. 6a. The hot seawater then flows into the first evaporation stage where the pressure is set lower. The sudden introduction of hot water into the chamber with lower pressure causes it to boil very quickly, almost flashing into steam. The vapor generated by flashing is condensed on tubes of heat exchangers that run through the upper part of each stage. The tubes are cooled by the incoming feed water going to the brine heater, thus preheating that water and recovering part of the thermal energy used for evaporation in the first stage. This process is repeated in up to 40 stages, whereas mostly around 20 stages are employed. To maximize water and energy recovery, each stage of an MSF unit operates at a successively lower pressure. The vacuum can be maintained by a steam ejector driven by high pressure steam or by a mechanical vacuum pump. Multi-stage flash (MSF) plants are widely used in the Middle East (particularly in Saudi Arabia, the United Arab Emirates, and Kuwait) and they account for 34% of the world's seawater desalination. A key design feature of MSF systems is bulk liquid boiling. This alleviates problems with scale formation on heat transfer tubes.

Large MSF units are often coupled with steam or gas turbine power plants for better utilization of the fuel energy by combined generation. Steam produced at high temperature and pressure by the fuel is first expanded through a turbine to produce electricity. The low to moderate temperature steam exiting the turbine is then used to drive a thermal desalination process. In this case, the capacity of the low pressure stage of the steam turbine to produce electricity is reduced with increasing temperature of the extracted steam. multi-stage flash plants are usually coupled to the cold end of a steam cycle power plant, extracting steam at 90–120 °C from the turbine to feed the brine heater of the MSF unit. If the temperature is above the condensation temperature of water at ambient pressure, special backpressure turbines are required for such a combined process. Moreover, the reduction of power generation with respect to a conventional condensing steam

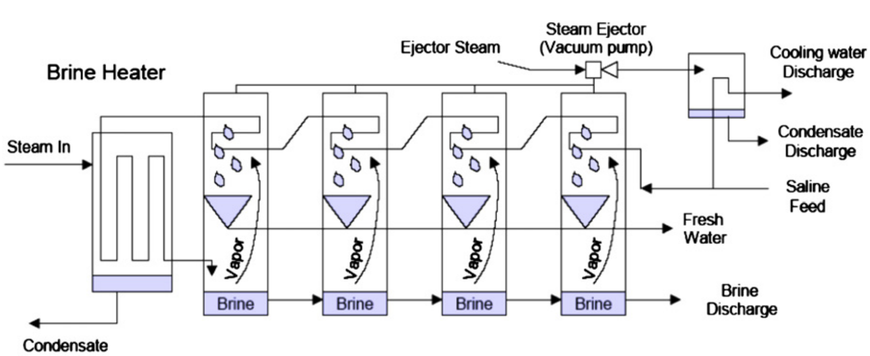

Fig. 5. Principle of multi-stage flash desalination (MSF) [6].

turbine working at 35–40 °C is considerable as indicated in Fig. 6b. On the other hand, an advantage of combined generation is that the condenser required for a conventional plant is substituted by the desalination unit, as in Fig. 6a. In this case, the feed water must include enough water for desalination and cooling.

The MSF process requires a considerable amount of steam for the evaporation process and also significant amounts of electricity to pump the large liquid streams as given in Table 4. Two different performance indicators are used: the performance ratio (PR) which is the ratio of product water and input heat, while the gained output ratio (GOR) is defined as the mass of water product per mass of heating steam. A typical gain output ratio for MSF units is 8. MSF is specially suited for desalination if the quality of the feed water is unfavorable (high salinity, temperature and contamination), as the system is very robust. A MSF plant has a typical heat requirement of 250–330 kJ/kg product. The specific electricity consumption is in the order of 3–5 kWh/m^3. To this, add a loss of electricity from the steam turbine due to the higher cold end temperature equivalent to 6–8 kWh/m^3 [6].

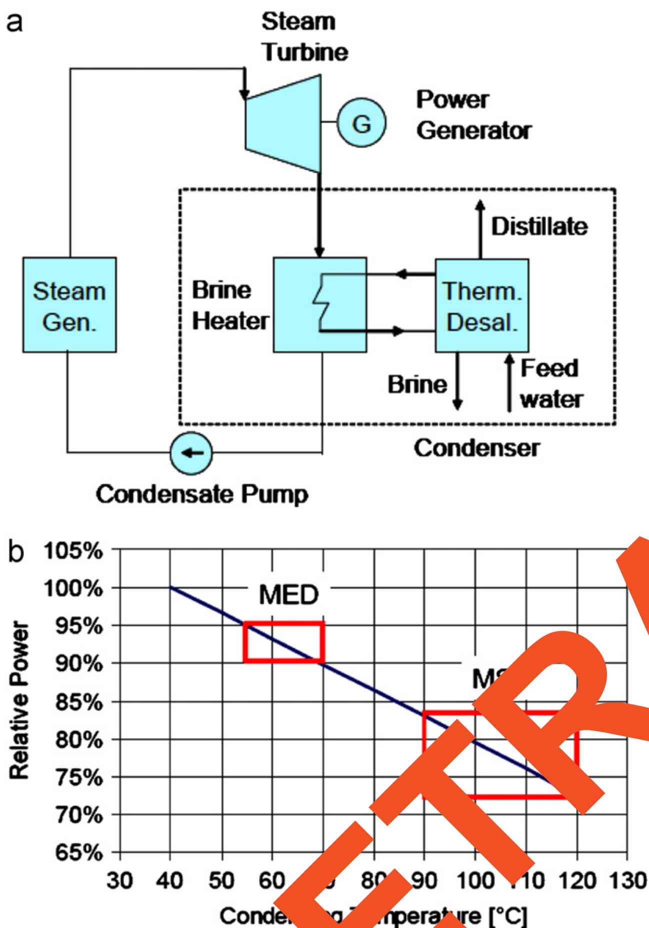

Fig. 6. (a) Principle of subs[titution of t]he con[dens]er [of a] steam cycle power plant by a thermal desalination [unit] [5,6]. (b) Typica[l red]uction of steam turbine power capacity at increasin[g co]ndensi[ng t]emperature. The rectangle show the typical operating range of ME[D an]d M[SF] [illegible].

2.2. Multi-effect desalination (MED)

Multi-effect desalination (MED) is also a thermal distillation process. As indicated in Fig. 7, the feed water is sprayed or otherwise distributed onto the evaporator surf[ace] (usually tubes) of different chambers (effects) in a thin film t[o] promo[te] evaporation after it has been preheated in the upper se[ctio]n of each c[ha]mber. The evaporator tubes in the first effect are heate[d by] steam e[xtr]acted from a power cycle or from a boiler. T[he] steam [pro]duc[ed] in the first effect is condensed inside the e[vapora]tor tubes [of the] next effect, where again vapor is produced. T[he] surfa[ces] of all the other effects are heated by the steam produ[ced] in [the] precedi[ng] effect. Each effect must have a lower pressu[re] than the [prece]d[in]g one. This process is repeated within up [illegible] effects. The [st]eam produced in the last effect is condensed in a se[para]te heat exchanger called the final condenser, which [is c]ooled by [the] incoming sea water, which is then used as pr[ehe]ated feed water [for] the desalination process. MED has gained a[tte]ntion due t[o] the better thermal performance compared to MSF. [In] princip[le] MED plants can be configured for high tempera[ture or] low t[em]perature operation. At present, they operate at top brine [tem]peratures below 70 °C to limit scale formation and [cor]rosion. The top brine temperature can be as low as 55 °C [whi]ch helps to reduce corrosion and scaling, and allows the use of low-grade waste heat. If MED coupled to a steam cycle, the power losses will be much lower than those obtained when coupling a MSF plant (Fig. 6b), and even standard condensing turbines may be used instead of back-pressure turbines.

The MED process can have several different configurations according to the type of heat transfer surface (vertical tube falling film, vertical tube climbing film, horizontal tube falling film, plate heat exchanger) and the direction of the brine flow relative to the vapor flow (forward, backward, or parallel feed). MED systems can be combined with heat input between stages from a variety of sources, e.g. by mechanical (MVC) or thermal vapor compression (TVC). MED-TVC systems may have thermal performance ratios (similar to the gained output ratio) up to 17, while the combination of MED with a lithium bromide-water absorption heat pump yielded a thermal performance ratio of 21.

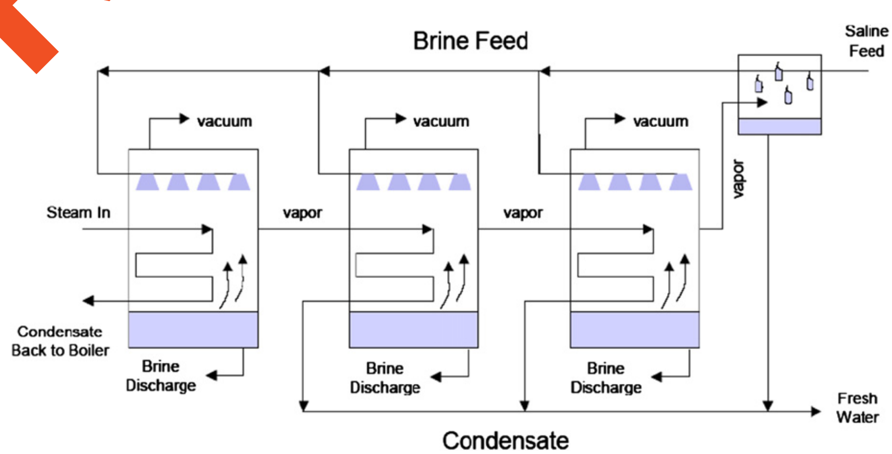

Fig. 7. Principle of multi effect desalination (MED) [6,7].

When coupling MED with the cold end of a steam cycle power plant, MED plants (without TVC) typically have a heat consumption of 190–390 kJ/kg in the form of process steam at less than 0.35 bar that is withdrawn from the steam turbine, and a specific electricity consumption of 1.5–2.5 kWh/m^3, mainly for pumping and control, which are fairly independent from raw water salinity, contamination or temperature. MED-TVC plants are driven with motive steam above 2 bars, mostly between 10 and 20 bar.

2.3. Reverse osmosis (RO)

Reverse osmosis (RO) is a membrane separation process that recovers water from a saline solution pressurized to a point greater than the osmotic pressure of the solution (Fig. 8). In essence, membrane filters hold back the salt ions from the pressurized solution, allowing only the water to pass. RO membranes are sensitive to pH, oxidizers, a wide range of organics, algae, bacteria, deposition of particulates and fouling. Therefore, pre-treatment of the feed water is an important process step and can have a significant impact on the cost and energy consumption of RO. Recently, micro-, ultra- and nano-filtration has been proposed as an alternative to the chemical pre-treatment of raw water in order to avoid contamination of the seawater by the additives in the surrounding of the plants. RO post-treatment includes removing dissolved gases (CO2), and stabilizing the pH via the addition of Ca or Na salts, and the removal of dangerous substances from the brine.

Pressurizing the saline water, accounts for most of the energy consumed by RO. Since the osmotic pressure, and hence the pressure required to perform the separation is directly related to the salt concentration, RO is often the method of choice for brackish water, where only low to intermediate pressures are required. The operating pressure for brackish water systems ranges from 10–15 bar and for seawater systems from 50 to 80 bar (the osmotic pressure of seawater with a salinity of 35 g/kg is about 25 bar) [6].

2.3.1. RO Energy recovery (Fig. 9)

Electricity consumption is a main cost component of the overall water production cost of SWRO. The RO reject stream (concentrate) contains most of the energy supplied to the seawater feed in the desalination process by the high pressure pump. Consequently recovery of this energy and its utilization to reduce the overall energy demand of SWRO is one of the major optimization issues during the design of a RO seawater desalination plant. Today, there are various energy recovery techniques available on the market. All technologies apply the basic principle of exchanging energy between the reject stream and the feed seawater stream. Available systems for energy recovery are summarized as follows:

- Energy Recovery Turbine (ERT), mostly with Pelton wheels.
- Pressure Exchanger (PX), which is an isobaric device that uses a rotating ceramic rotor as the main element and allows the feed and concentrate to have direct contact.

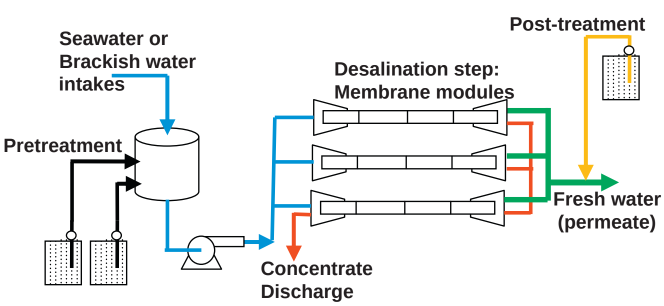

Fig. 8. Principle of desalination by reverse osmosis (RO) [6,8–10].

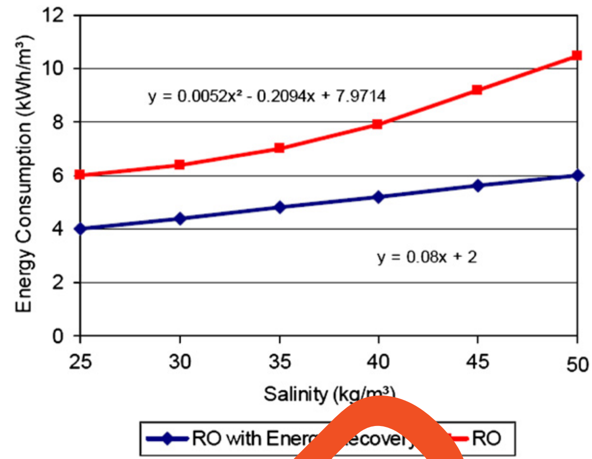

Fig. 9. Specific electricity consumption of reverse osmosis plants with and without energy recovery system as function of raw water salinity [6].

Table 3
Typical efficiency of energy recovery devices [4,8].

Energy recovery system	Efficiency%
Francis turbine	76
Pelton turbine	87
Turbo charger	85
Work exchanger	96
Pressure exchanger	96

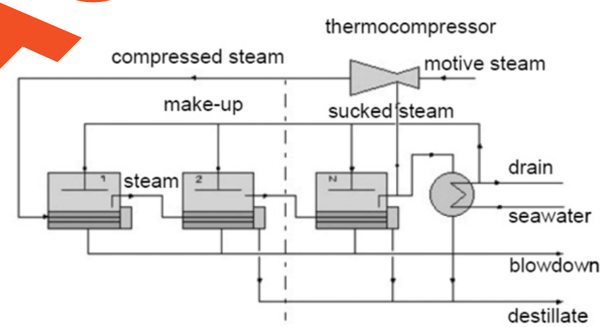

Fig. 10. Principle of thermal vapor compression (TVC) [6,7].

- Dual Work Exchanger Energy Recovery (DWEER), which is an isobaric device that uses pistons and valves to separate seawater feed and the concentrate return.
- Turbocharger, which is a turbine driven centrifugal pump, mostly applied.

To choose and compare between the different types of energy recovery devices, the efficiency figures are given in Table 3.

2.4. Thermal vapor compression (TVC)

Vapor compression is added to a multi-effect distiller in order to improve its efficiency. Vapor compression processes rely on the reuse of vapor produced in the distiller as heating steam after recompression. The vapor produced in one stage is partially recompressed in a compressor and used to heat the first cell. The vapor is compressed either by a mechanical compressor (mechanical vapor compression, MVC) or by a steam ejector (thermal vapor compression, TVC). For thermal vapor compression, motive steam at higher pressure is withdrawn from another process, e.g. a steam power cycle or industrial process steam as shown in Fig. 10.

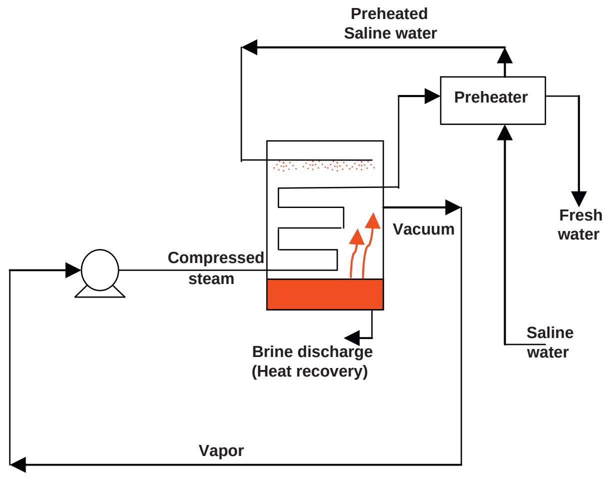

Fig. 11. Single stage mechanical vapor compression desalination process (MVC) [6].

2.5. Mechanical vapor compression (MVC)

Mechanical vapor compression processes are particularly useful for small to medium plants. MVC units are typically range in size up to about 3000 m^3/day. While TVC units may range in size up to 36,000 m^3/day. MVC systems have between one and three stages. Most of them only have a single stage. While TVC systems have several stages. This difference arises from the fact that the pressure and temperature increase by the mechanical compressor and its capacity are limited. The operation principle of mechanical vapor compression is indicated in Fig. 11.

3. The key Elements of desalination plants

The five key elements of a desalination system used for either brackish water or seawater desalination are as follows [[illegible],10,11]:

1. Intakes: is the structures used to extract source water and convey it to the process system;
2. Pretreatment: is a removal of suspended solids and control of biological growth, to prepare the source water for further processing;
3. Desalination: is the process that removes dissolved solids, primarily salts and other inorganic constituents from a water source;
4. Post-treatment: is the addition of chemicals to the product water to prevent corrosion of downstream infrastructure piping; and
5. Concentrate management: is the handling and disposal or reuse of waste residuals from the desalination system.

4. Hybrid desalination plants

4.1. Hybridization MSF-RO plant

Hybridization of SWRO and MSF technology was considered to improve the performance of MSF and to reduce the cost of the produced water. Integration of the three processes of MSF, MED, and RO desalination technologies could be made at different levels through which the resultant water cost will depend on: the selected configuration and the cost of materials of construction, equipment, membrane, energy, etc. Thus, the capital and annual operating costs were calculated. It was reported that for all plant capacities, integrated hybrid systems resulted in most cost effective solution. As example, Fujairah hybrid MSF-RO plants is the largest seawater desalination and power plant in the world that has been implemented up to now (hybrid configuration of thermal processes (MSF) and reverse osmosis(RO)). The Fujairah plant due to hybridization generates 500 MW net electricity for export to the grid, and 662 MW gross is used for water production of 455,000 m^3/d [6,7].

4.2. Hybridization of nano-filtration(NF) and MSF

Removal or significant reduction of hardness in seawater, lowering of TDS and removal of turbidity from the feed to seawater desalination plants should lead to an improvement in the conventional seawater desalination processes by: lowering of their energy requirement and chemical consumption, increasing water recovery with the ultimate benefit of lowering the cost of fresh water production. This has been shown to be feasible by a combination of NF with the conventional seawater desalination processes. Nano-filtration membrane softening technology increases the capacity of existing MSF plant from nominal 22,700 m^3/d to 32,800 m^3/d (+40%) [6–9].

4.3. Hybridization of nuclear-powered MSF-RO

Rising Costs, uncertain availability and environmental concerns of fossil fuel have led to the need to use renewable and other sustainable energy sources, including nuclear. Desalination of seawater using nuclear energy has been demonstrated. Water cost from nuclear seawater desalination is in the same range as costs associated with fossil-fueled desalination. Utilizing waste heat from nuclear reactors has been used to reduce the cost of nuclear desalination. Safety precautions have to be considered including the possibility of radioactive contamination. Nuclear desalination has the potential to be an important option for economic and sustainable supply of large amounts of desalinated water.

MSF plants often use low-pressure steam as an energy source while RO plants are operated by electrical power to derive the high-pressure pumps and other plant auxiliaries. RO power consumption depends mainly on water recovery and the working pressure. Low pressure and temperature steam extracted from nuclear heating reactors may be used for supplying the necessary energy to derive the MSF units. Electricity can be generated from the nuclear power reactor to derive the high-pressure pumps of the RO desalination plants. Coupling RO and MSF with nuclear steam supply system will yield some economical and technical advantages. The hybrid RO-MSF system has potential advantages of a low power demand, improved water quality and possible lower running cost as compared to stand-alone RO or MSF.

The world's first nuclear-powered MSF-RO hybrid desalination plant is established at MAPS, Kalpakkam, India. This plant is based on conventional MSF technology developed in India. Although this plant is a small capacity demonstration plant (6300 m^3/d capacity hybrid MSF-RO), it has provided very useful data for design of large size nuclear desalination plants in future. The experience has indicated safe operation of such plants for providing water for domestic as well as industrial needs.

5. Pre-selection of desalination technologies

Table 4 shows some of the characteristics of the four leading desalination technologies. The purpose of this comparison is to select the most appropriate thermal and mechanical desalination method for the combination with CSP, and to find a plausible combination that could be representative for large scale dissemination.

Comparing MSF and MED, it becomes clear that MED is more efficient in terms of primary energy and electricity consumption and has a lower cost. Moreover, the operating temperature of MED is lower, thus requiring steam at lower pressure (if connected in co-generation to a steam cycle power plant). Thus, the

Table 4
Characteristics of the two main thermal desalination technologies and the two main mechanical desalination technology options. The figures refer to seawater as the raw water source.

Energy used	Thermal		Mechanical	
Process	MSF	MED/TVC	MVC	RO
State of the art	Commercial	Commercial	Commercial	Commercial
World Wide Capacity 2004 (Mm^3/d)	13	2	0.6	6
Heat consumption (kJ/kg)	250–330	145–390	–	–
Electricity consumption (kWh/m^3)	3–5	1.5–2,5	8–15	2.5–7
Plant cost ($\$/m^3/d$)	1500–2000	900–1700	1500–2000	900–1500
Time to commissioning (months)	24	18–24	12	18
Production unit capacity (m^3/d)	<76000	<36000	<3000	<20000
Conversion freshwater/seawater	10–25%	23–33%	23–41%	20–50%
Max. top brine temperature (°C)	90–120	55–70	70	45 (max)
Reliability	Very high	Very high	High	Moderate for seawater
Maintenance (cleaning per year)	0.5–1	1–2	1–2	Several times
Pre-treatment of water	Simple	Simple	Very simple	Demanding
Operation requirements	Simple	Simple	Simple	Demanding
Product water quality (ppm)	<10	<10	<10	200–500

Table 5
Power consumption of desalination technologies.

Desalination technology	Total electric energy	Heat consumption
MSF	3–5 KWh/m^3	250–330 KJ/Kg
MED/TVC	1.5–2.5 KWh/m^3	145–390 KJ/Kg
MVC	8–15 KWh/m^3	–
RO	2.5–7	–

combination of CSP with MED will be more effective than combination of CSP and MSF desalination.

Thermal vapor compression is often used to increase the efficiency of an MED process, but it requires steam at higher pressure (if connected to a steam power plant).

Comparing the mechanical driven desalination options, reverse osmosis has a lower electricity consumption and [illegible] a product of water than the mechanical vapor compression method.

The much lower primary energy consumption of RO and the slightly lower cost compared to MED suggests that RO might be the preferred desalination technology anyway. However, if MED is coupled to a thermal power plant, it replaces the cost of the condensation unit of the steam cycle and partially uses waste heat from power generation for the desalination process. In this case, not all the primary energy used must be accounted for the desalination process, but only the portion that is equivalent to a reduction of the amount of electricity generated in the plant when compared to a conventional cooling at lower temperature, and of course the direct power consumption of the MED process.

Processes combining thermal and mechanical desalination may lead to more efficient future desalination systems.

Finally, more detailed analysis of a combination with concentrated solar power (CSP) under different environmental and economic site conditions will be considered in the following sections.

6. Key energy consumption figures

In this section, the power consumption figures and energy data of desalination technologies are summarized in Tables 5 and 6 respectively.

7. Potential of solar energy

Energy experts expect that in the year 2050, over 50% and 80% of all electricity could be generated by renewable energy [9,10]. Among the potential sources of renewable energy, solar thermal power plants are considered to be one of the most economic.

The understanding of solar technology and its associated challenges will provide a suitable basis to recognize advantages and drawbacks. The annual horizontal solar energy available (kWh/m^2) and relative peak value (W/m^2) in some countries are given in Table 7 [10]. The following sections will outline various existing solar technologies [10–14].

Assessment of solar radiation resources in different cities of KSA is given in Table 8. The daily and annual distribution pattern of solar energy at given locations are essential not only for assessing the economic feasibility of solar energy utilization, but also for the thermal design and environmental control of buildings and greenhouses.

8. Different combination between RES and desalination systems

There are numerous renewable energy sources (RES)-desalination combinations have been identified and tested in the framework of ongoing research for innovative desalination processes [1–3]. Table 7 and Fig. 12 show the distribution of renewable energy powered desalination technologies [2]. Energy requirement in the form of thermal as well as electrical energy can make up between 50% and 70% of the total operating cost and it is thus not surprising that many of the large-scale thermal desalination plants are co-located with power stations or industries with thermal process energy waste.

RO desalination unit can be coupled with different types of renewable energy. Table 9 summarizes several studies which were presented with various possible combinations and Table 10 presents the corresponding costs. As shown in Table 10, the cost of desalinated water depends on few factors including plant capacity, RES/RO systems design, feed water quality, site location, etc.

There are mainly two PV driven membrane processes, reverse osmosis (RO) and electro-dialysis (ED). Both techniques are commercially available technologies.

8.1. Photovoltaic and RO combination (PV/RO)

Electricity which is produced by PV is direct current (DC). It can be used by any electrical appliances that uses DC or to charge a battery. However, most of electrical appliances use active current (AC) to operate. In this case, an inverter is needed to convert DC to AC. Electricity generated by PV is direct, simple, maintenance-free, quiet, clean, renewable and economic in rural areas. Solar modules

Table 6
Key energy data for desalination technologies [6–9].

	MSF	MED	SWRO
Max. concentrate temp., °C	< 115–120	< 70	< 45
Typical steam P, bar	2.5: 3	2.5: 3(MED-TVC) 0.3–0.5(Plain MED)	–
Typical present day heat demand, MJ/m^3	233–258 corresponding to at PR of 9: 10 kg/2326 KJ	233–258 corresponding to PR of 9: 10 kg/2326 KJ	–
Typical present day electricity demand, KWH/m^3	3–5	1.5–2.5	3–5

Table 7
The Annual horizontal solar energy available in some countries [10].

Country	Annual solar energy KWh/m^2	Peak radiation W/m^2
Yemrn	2170	940
Saudi Arabia	2160	940
Oman	2140	930
Egypt	2050	1030
Jordan	2050	1020
Libya	2010	1040
U.A. Emirates	1980	910
Israel	1930	1010
Syria	1910	1040
Malta	1900	1040
Morocco	1860	960
Algeria	1840	950
Tunisia	1750	980

Table 8
Solar radiation resources in different cities of KSA [12].

Station	North latitude	East longitude	Altitude m	Global Radiation Wh/ m^2	Sunshine Duration hours
Abha	18° 13'	42° 29'	2200	5824	8.7
Al-Hofuf	25° 30'	49° 34'	160	5671	8.7
Al-Qatif	26° 33'	50' 00'	8	[illegible]	[illegible]
Bisha	20° 01'	42° 36'	1020	[illegible]	[illegible]
Derab	24° 25'	46° 34'	0	[illegible]	[illegible]
Hail	27° 28'	41° 38'	1010	[illegible]	9.4
Madina Al-Munawara	24° 31'	39° 35'	590	[illegible]	9.1
Najran	17° 33'	44° 14'	[illegible]	6936	9.1
Qurayyat	31° 20'	[illegible]	[illegible]	5562	9.0
Riyadh	24° 34'	[illegible]	[illegible]	5132	9.2
Sakaka	29° 58'	40° 12'	[illegible]	[illegible]	9.0
Tabuk	28° 23'	[illegible]	[illegible]	[illegible]	9.1
Taif	[illegible]	[illegible]	[illegible]	5429	8.9
Yabrin	[illegible]	[illegible]	[illegible]	5631	9.1

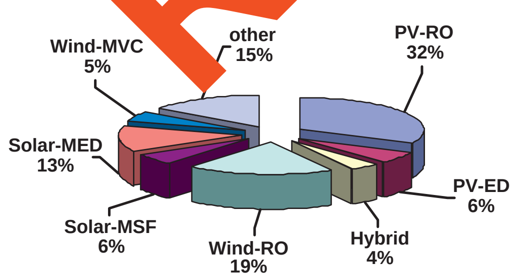

Fig. 12. Distribution of renewable energy powered desalination technologies [2].

are connected together to generate more power depending on the needs. The flow diagram of simple PV-RO unit is shown in Fig. 13

The (PV)-powered reverse-osmosis (RO) desalination system is considered one of the most promising technologies in producing fresh water from both brackish and sea water, especially for small systems located in remote areas [19,26,27].

Table 9
General Combinations technologies of RESand desalination methods [2].

Renewable energy sources 1-Solar										
PV			Solar thermal							
Electricity			Heat			Shaft			Electricity	
RO	ED	MVC	TVC	MED	MSF	MVC	RO	ED	RO	MVC
2-Wind					3-Geothermal					
Shaft		Electricity			Electricity			Heat		
MVC	RO	RO	ED	MVC	RO	ED	MVC	TVC	MED	MSF

Table 10
Water cost for desalination by renewable energies [11].

Combination	Water	Plant capacity (m^3/d)	Water cost (US$/m^3)	year
PV/BAT/RO	Seawater	12	27	1996
PV/BAT/RO		120	7.4	1996
PV/BAT/RO	Brackish water	250	6.7	1991
PV/RO	Seawater	1.5	2.95	2003
WIND/BAT/RO	Brackish water	250	2.7	2003
WIND/GRID/RO	Seawater	300	1.8	2002
PV/GRID/RO	Seawater		1.9	2005

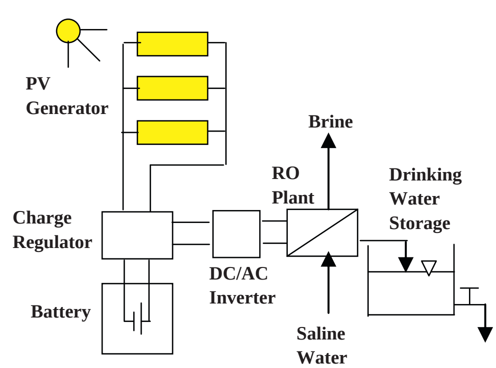

Fig. 13. Flow diagram for PV-BWRO system [19,26].

8.2. Combination options between desalination and CSP technologies

This section gives a review of the present state of the art of desalination and of concentrating solar power technologies, and shows the main options for a combination of both technologies for large scale solar powered seawater desalination. Three different technical mainstreams were addressed in Fig. 14: small-scale decentralized desalination plants directly powered by concentrating solar thermal collectors, concentrating solar power stations providing electricity for reverse osmosis membrane desalination (CSP/RO), and

combined generation of electricity and heat for thermal multi-effect desalination systems (CSP/MED). Multi-stage flash (MSF) desalination, although at present providing the core of desalted water in the middle east and north Africa (MENA) region, it has not been considered as viable future option for solar powered desalination. This is due to the high energy consumption of the MSF process.

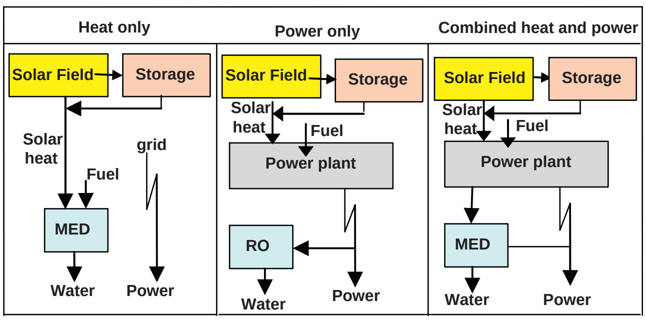

Fig. 14. Different configurations for desalination by concentrated solar power. Left: concentrating solar collector field with thermal energy storage directly producing heat for thermal multi-effect desalination. Center: power generation for reverse osmosis (CSP/RO). Right: combined generation of electricity and heat for multi-effect desalination (CSP/MED) [5–9].

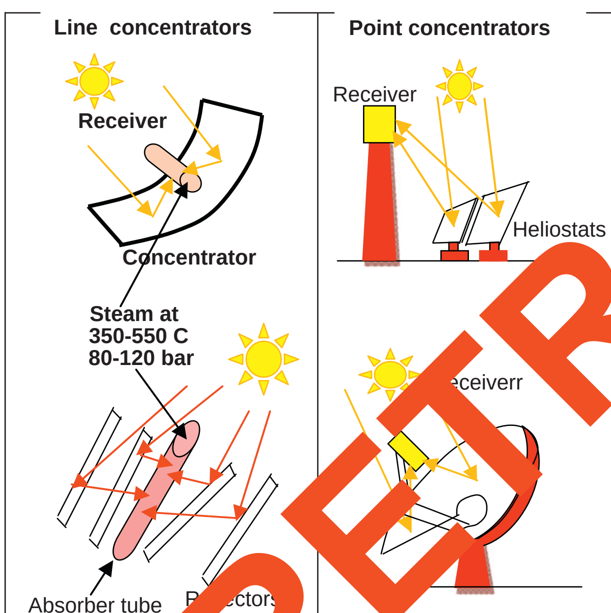

Fig. 15. The four mainstream CSP-technologies for the production of high-temperature solar heat for power generation and process steam: parabolic trough (upper left), linear Fresnel (bottom left), solar tower (upper right) and dish Stirling (bottom right) [11].

9. Concentrating solar power (CSP) technologies

The present study is giving more focus on concentrating solar thermal power generation because this is by far the most abundant and most reliable renewable energy resource in the MENA region. CSP will provide the core energy for large scale seawater desalination for the growing urban centers and mega-cities in the MENA region. Parabolic trough, linear Fresnel, solar tower and dish Stirling are the main types of CSP-technologies. These types and its performance data are shown in Fig. 15 and Table 11 respectively.

Concentrating solar thermal power technologies are based on the concept of concentrating solar radiation to provide high-temperature heat for electricity generation within conventional power plant using steam turbines, gas turbines or Stirling engines. For sun concentration, most systems use glass mirrors that continuously track the position of the sun. In the case of CSP, the sunlight is focused on a receiver that is specially designed to reduce heat losses. A fluid flowing through the receiver takes the heat away towards a thermal power cycle, where e.g. high pressure, high temperature steam is generated to drive a turbine. Air, water, oil and molten salt can be used as heat transfer fluids [6].

Parabolic troughs, linear Fresnel systems and solar towers can be coupled to steam cycles of 5 to over 200 MW of electric capacity, with thermal cycle efficiencies of 30–40%. Dish-Stirling engines are used for decentralized generation in the 10 kW range. The values for parabolic troughs have been demonstrated in the field. Today, these systems achieve annual solar-to electricity-efficiencies of about 10–15%, with the perspective to reach about 18% in the medium term.

A maximum efficiency of 21.5% for the conversion of solar energy into grid electricity was measured in a 30 MW plant in California [6]. Solar towers can achieve very high operating temperatures of over 1000 °C, enabling them to produce hot air for gas turbine operation. Gas turbines can be used in combined cycles, yielding very high conversion efficiencies of the thermal cycle of more than 50%.

Thermal power plants can be operated with fossil fuel as well as with solar energy. This hybrid operation has the potential to increase the value of CSP technology by increasing its power availability and decreasing its cost by making more effective use in power generation. Solar heat collected during the daytime can be stored in concrete, molten salt, ceramics or phase change media. At night, it can be extracted from the storage to run the power plant. Fossil fuels like oil, gas, coal and renewable fuels like biomass can be used for co-firing the plant, thus providing power capacity whenever required. This is a very important feature for the coupling with desalination processes, as they usually require steady-state energy input for smooth operation. There is also the possibility to by-pass steam directly from the solar field to the desalination plant, thus achieving a certain co-production of power demand and water. Moreover, high-temperature concentrated solar energy can be used for co-generation of electricity and process heat. In this case, the

Table 11
Performance data of various concentrating solar power (CSP) technologies [6].

	Unit capacity MW	Concentration	Peak solar efficiency	Annual solar efficiency	Thermal cycle efficiency	Capacity factor (solar)	Land use m^2/MWh/y
Trough	10–200	70–80	21% (d)	10–15% (d) 17–18% (p)	30–40% ST	24% (d) 25–90% (p)	6–8
Fresnel	10–200	25–100	20% (p)	9–11% (p)	30–40% ST	25–90% (p)	4–6
Power tower	10–150	300–1000	20% (d) 35% (p)	8–10% (d) 15–25% (p)	30–40% ST 45–55% CC	25–90% (p)	8–12
Dish-stirling	0.01–0.4	1000–3000	29% (d)	16–18% (d) 18–23% (p)	30–40% Stirl. 20–30% GT	25% (p)	8–12

(d) = demonstrated, (p) = projected, ST: steam turbine, GT: gas turbine.
CC: Combined Cycle. Solar efficiency = net power generation/ incident beam radiation.
Capacity factor = solar operating hours per year/8760 hours per year.

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primary energy input is used with efficiencies of up to 85%. Possible applications can cover the combined production of industrial heat, district cooling and sea water desalination. All CSP concepts have the perspective to expand their time of solar operation to base load using thermal energy storage and larger collector fields (except the Integrated Solar Combined Cycle System (ISCCS) which has a limited solar share of less than 20%).

To generate one Megawatt-hour of solar electricity per year, a land area of only 4–12 m^2 is required [6]. This means, that one km^2 of arid land can continuously generate as much electricity as any conventional 50 MW coal or gas fired power station.

From each km^2 of desert land, about 250 GWh of electricity can be harvested each year using concentrating solar thermal power technology (based on solar irradiance 2400 kWh/m^2/y × 11% Annual Solar-Electric net Efficiency × 95% Land Use (Linear Fresnel)). This is over 200 times more than what can be produced per square kilometer by biomass or 5 times more than what can be generated by the best available wind and hydropower sites. Each year, each square kilometer of land in MENA receives an amount of solar energy that is equivalent to 1.5 million barrels of crude oil (solar irradiance 2400 kWh/m^2/y × 1 million m^2/km^2: 1600 kWh/bbl heating value = 1.5 million bbl/km^2/y). A concentrating solar thermal power plant of the size of Lake Nasser in Egypt (Aswan) would harvest energy equivalent to the present Middle East oil production(Lake Nasser has 6000 km^2 × 1.5 million bbl/km^2/y = 9 billion bbl/y = Middle East oil production).

A CSP plant covering one square kilometer of desert land will deliver enough energy to desalinate over the whole year an average of 165,000 m^3/day, which is equivalent to a major contemporary desalination unit (solar irradiance 2400 kWh/m^2/y × 11% CSP efficiency × 95% land use: 4.2 kWh/m^3 RO power consumption: 365 day/y = 0.165 m^3/m^2/day × 1 million m^2/km^2 = 165,000 m^3/km^2/day) [6].

The main characteristics that make concentrating solar power a key technology for a future renewable energy and also a key energy resource for seawater desalination in MENA are:

- it can deliver firm power capacity as requested by demand,
- its natural resource is easily accessible and practically unlimited,
- it can be used for combined generation of heat and power for cooling and desalination,
- its cost is already lower today than world market prices of fuel oil and rapidly decreasing with further market expansion,
- their thermal storage capability and hybrid operation with fuels allows CSP plants to provide power on demand. Their availability and capacity credit is considered to be well over 90%. Availability in the Californian SEGS has been reported to be better than 99%. CSP plants can be built from several kW to several 100 MW capacities [6].

The first CSP plants were installed in California in the mid 1980s, when fuel costs were high and tax credits allowed for a commercial erection and operation of a total of nine plants at capacity of 14–80 MW each. CSP electricity costs came down dramatically from 27 (in 1986) to 12 $-cents per kWh in 1991 [6].

9.1. Concentrating solar power for steam turbines

As shown in Fig. 16, line focusing systems use trough like mirrors and specially coated steel absorber tubes to convert sunlight into useful heat. The troughs are normally designed to track the sun along one axis, predominantly north-south. To generate electricity, a fluid flowing through the absorber tube (usually synthetic oil or water/steam) transfers the heat to a conventional steam turbine power plant. Recently, molten salts have also been discussed as heat transfer fluid. Concentrating the sunlight by about 70–100 times, typical operating temperatures are in the range of 350–550 °C. Plants of 200 MW rated power and more can be built using this technology. Hybrid operation with all kinds of fossil or renewable fuels is possible. In order to increase the number of solar operating hours beyond the times when the sun shines, the collector field can be designed to provide, under standard conditions, more energy than the turbine can accept. This surplus energy is used to charge a heat storage, which can provide the required energy input to the turbine system during periods of insufficient solar radiation. Heat storage may consist of two large tanks, each containing a molten nitrate salt mixture as storage medium with the necessary heat capacity for several hours of full load operation of the turbine. Heat is transferred from or to the heat transfer fluid of the collector via a heat exchanger. The liquid molten salt is pumped through this heat exchanger from the cold tank to the hot tank during charging and vice versa during discharging periods as shown in Fig. 17.

A first plant of this type with 50 MW rated power using synthetic oil as heat transfer fluid and a molten salt storage with 7.5 full load hours capacity was built in the Spanish Sierra Nevada. On July 2006,

Fig. 16. Principle of line focusing concentrating solar collector systems [6]. (a) Animation of a linear Fresnel type concentrating solar thermal collector field for direct steam generation. (b) Parabolic trough solar field of the 5 × 30 MW solar electricity generating system (SEGS) in Kramer Junction, California.

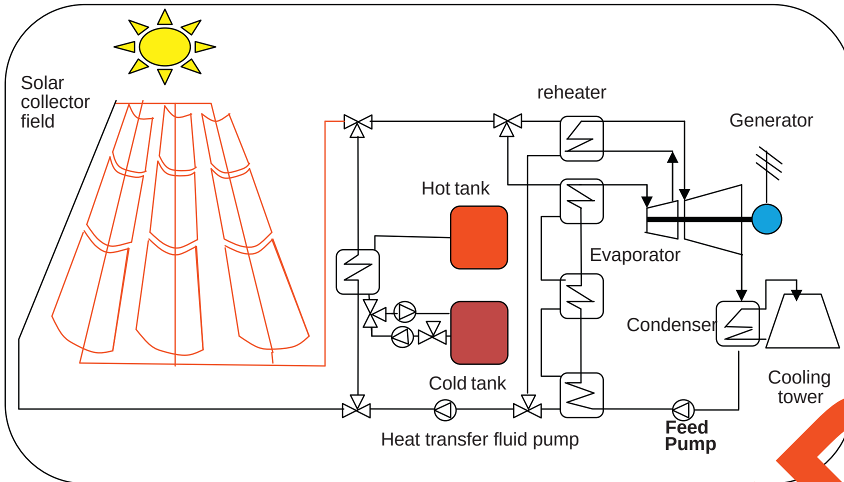


Fig. 17. Line focusing concentrating collector coupled with a steam cycle power plant [6].

construction started near Almería/Spain for the 50 MW_{el} parabolic trough plant ANDASOL 1, which was followed by identical plants ANDASOL 2 & 3 in the next couple of years. Its collector area of over 510,000 m^2 makes ANDASOL 1 the world's largest solar power plant. It was designed to generate approximately 179 GWh of electricity per year to supply some 200,000 people with environmentally friendly solar electricity. Another 64 MW parabolic trough plant was commissioned in Nevada in summer 2007. Finally, there is a world-wide capacity of about 1000 MW to be commissioned within the coming 5 years period [6].

The present parabolic trough plant design uses a synthetic oil to transfer energy to the steam generator of the power plant cycle. Direct solar steam generation in the absorber tubes of parabolic trough collectors is a promising option for improving the economy of solar thermal power plants. Steam temperatures up to 400 °C at 100 bar pressure have been reached within the framework of a European project undertaken over 6000 operating hours at the Plataforma Solar de Almería, Spain. The test loop with 700 m length and an aperture of 5.70 m has been designed and constructed for the purpose of demonstrating safe operation and controllability under constant and transient operating conditions.

Linear Fresnel systems have recently been developed by several companies with the goal to achieve a more simple design and lower cost than the parabolic trough. In a Fresnel system, the parabolic shape of the trough is split into several smaller, relatively flat segments. These are put on a horizontal rag and connected at different angles to a rod-bar that moves them simultaneously to track the sun during the day. Due to this arrangement, the absorber tube can be fixed above the mirrors in the center of the solar field, and does not have to be moved together with the mirror during sun-tracking. The Fresnel structure allows for a very light design, with the forces absorbed by the four corners of the total structure. Large screws instead of pylons are literarily screwed into the ground and hold the lateral bars of the Fresnel structure. While parabolic troughs are fixed on central pylons that must be very strong and heavy in order to cope with the resulting central forces.

Comparing with the existing parabolic trough, the linear Fresnel collector system designed by Novatec–Biosol shows a weight reduction per square meter of 80%. This structure reflects not only a lower cost, but also leads to lower life cycle emissions. On the other hand, the simple optical design of the Fresnel system leads to a lower optical efficiency of the collector field, requiring about 33% more mirror aperture area for the same solar energy yield compared to the parabolic trough [6].

In terms of integration of the solar field to its environment, the Fresnel system has considerable advantages over parabolic troughs. Land use is much better, as the distances between mirrors are much smaller. The collector aperture area covers between 80% and 95% of the required land, while for the parabolic trough, only 30% of the land is covered by mirrors, because the distances between the single parabolic-trough-rows are necessary to avoid mutual shading. Land use efficiency of a linear Fresnel is thus about 3 times higher than that of a parabolic trough. Considering the lower optical efficiency of the Fresnel (2/3 of that of a parabolic trough), this leads to a roughly two times better solar energy yield per square meter of land of the Fresnel system when compared to a parabolic trough. This fact may not be of much importance in remote desert areas. But it may be of importance when integrating CSP to industrial or tourist facilities, or placing CSP near the coast and close to urban centers.

The flat structure of the Fresnel segments can be easily integrated to industrial or agricultural uses. In the hot desert, the shade provided by the Fresnel segments may be a valuable extra service provided by the plant. It could cover all types of buildings, stores or parking lots, protect certain crops from excessive sunshine and reduce water consumption for irrigation.

A parabolic trough solar field must be free of vegetation, because concentrated sunlight could ignite dry grass and lead to grass fires. Especially in those plants that use synthetic oil as heat transfer fluid, this would constitute a significant danger. There is no such danger using Fresnel systems, and thus, the land below can be used for pasture or agriculture of low growing crops.

9.2. Concentrating solar power for gas turbines

Solar towers use a large field of two-axis tracking mirrors (heliostats) that reflect the sunlight to a central receiver on top of a tower, where the concentrated solar energy is converted to high temperature heat as indicated in Fig. 18. The typical optical concentration factor ranges from 200 to 1000, and plant sizes of 5–150 MW are feasible. The high solar fluxes impinging on the receiver (average values between 300 and 1000 kW/m^2) allow working at high temperatures over 1000 °C and to integrate thermal energy into steam cycles as well as into gas turbines and combined cycles. Solar towers with central receiver systems can be integrated in fossil plants for hybrid operation in a wide variety of options and have the potential to generate electricity with high annual capacity factors by using thermal storage. Solar towers can be used for steam generation, with a 10 MW plant being recently realized in Spain (Planta Solar 10 near Sevilla) and another one being is available in Solar Tres. In the steam cycle market segment, those systems will have to compete with the

Fig. 18. Principle of a point focusing solar tower system (Plataforma Solar de Almeria, Spain) [6].

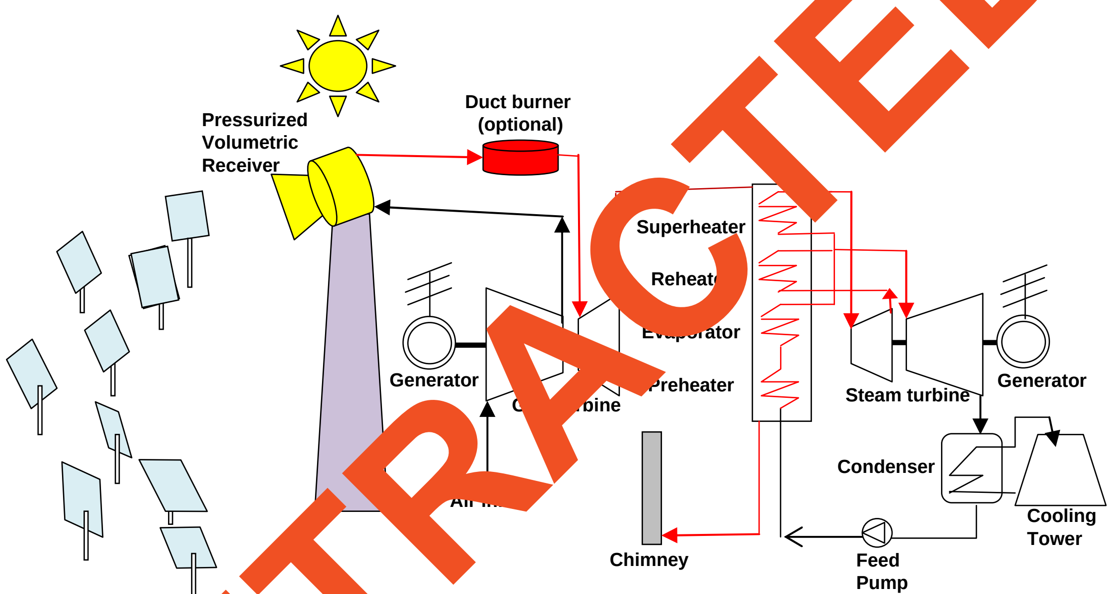


Fig. 19. Solar tower used for gas turbine operation in a combined cycle power plant [6].

established trough technology, and hence, their technical and economic performance characteristics will have to be equal or superior to those of the trough system [6].

High efficiencies can be achieved with solar-heated gas turbines, which may be increased further in combined cycle processes as given in Fig. 19. These systems have additional advantages that they can also be operated with natural gas during start-up and with a high fossil-to-electric efficiency when solar radiation is insufficient. Hence, no backup capacities of fossil fuel plants are required and high capacity factors are provided all year round. In addition, the consumption of cooling water is reduced significantly compared to steam cycle systems.

The high temperatures required for gas turbine operation and the heat transfer using air require a different receiver concept than the absorber tubes used in linear concentrating systems.

Volumetric receivers do not absorb the concentrated solar radiation on an outer tube surface, but within the volume of a porous body. Air can be used as heat transfer medium which is flowing through that porous material, taking away the heat directly from the surface where it has been absorbed. Due to the excellent heat-transfer characteristics, only a small temperature gradient between the absorber material and the air exists,

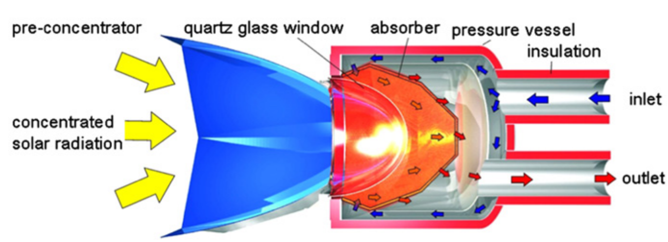


Fig. 20. Pressurized air heated by solar energy using a volumetric receiver [6].

and thermal losses are reduced. Also, the heat flux density can be much higher than in gas cooled tube receivers.The porous material can be a wire mesh for temperatures up to 800 °C or ceramic material for even higher temperatures. There are two principal designs of volumetric receivers: the open or atmospheric volumetric receiver uses ambient air sucked into the receiver from outside the tower. The heated air flows through the steam generator of a Rankin cycle. The second concept is the closed or pressurized volumetric receiver that uses pressurized air in a receiver closed by a quartz window as indicated in Fig. 20.

This system can heat pressurized air coming from the compressor of a gas turbine power plant. A first pilot system has been installed and tested on the Plataforma Solar de Almería in Spain, with the following targets being reached:

- receiver outlet temperature 1050 °C with pressures up to 15 bar,
- 90% secondary concentrator efficiency,
- external cooling of window to maintain glass temperatures below 800 °C, with negligible thermal losses,
- demonstration of electric power output of 230 kW were achieved

9.3. *Concentrating solar power for combined electricity and heat*

By the end of 2006, a feasibility study was finished by a Jordanian/German consortium to assess the technical and economical feasibility of an integrated production of 10 MW of power, 10,000 t/day of desalted water and 40 MW cooling capacity for the Ayla Oasis Hotel Resort in Aqaba, Jordan. The system allows for a very efficient use of fossil fuel and uses concentrated solar energy as fuel saver. A parking lot of 110,000 m^2 was designated for the integration of the solar field. A linear Fresnel concentrating collector field was selected as solar component. The reason is that the flat Fresnel structure can be fitted better than parabolic trough and the solar energy yield of the Fresnel field on the limited space is roughly twice of that of an equivalent parabolic trough field [6]

The conventional solution for the hotel resort would have been purchasing electricity and water from the public grid and cooling by conventional rooftop compression chillers. As electricity and water are already limited in Aqaba, additional power plant capacity for power and desalination would have been required. As shown in Fig. 21, the conventional supply of the required commodities would require a natural gas consumption of 85 MW.

The insecurity of future prices for fossil fuels has led to the investigation of the feasibility of an alternative power plant concept for on-site production based on the combined generation of electricity and heat for absorption cooling and multi-effect desalination. The absorption chillers are used for base load operation during the holiday season. While the compression chillers are only used for peaking and intermittent demand. A cold water district cooling grid will be used to distribute the cooling power from the central plant to the different users in several hotels, residential areas and commercial centers and for the technical operation of the resort. The result of the analysis showed that the integrated process require 35% less fuel input, due to the better efficiency of combined generation and the solar fuel saver as sketched in Fig. 22.

An advantage of onsite production of commodities like power, water and cooling is that the production cost competes with purchase prices rather than with the production cost of large conventional power plants that include distribution and public infrastructure. With revenues of 0.10 $/kWh for electricity, 0.04 $/kWh for cooling and 1.50 $/m^3 for water, the project can be realized with a good internal rate of return without depending on subsidies [6].

In general, there is a good coincidence of solar energy and cooling demand (50% of the electricity load in the MENA-Region is caused by air-conditioning due to intensive solar radiation), which allows for a very efficient use of the solar energy and for fuel saving specifically during peak load times. This innovative concept opens considerable market opportunities for the unsubsidized use of solar energy.

9.4. *Pre-selection of CSP technologies*

In general, all CSP technologies can be used for the generation of electricity as well as for the desalination of seawater. Tables 12 and 13 and Fig. 23 include characteristics and cost figures as a guide for selection. The scope of pre-selection within this study is to find a CSP-technology that can be used as reference with respect to performance, cost and integration with seawater desalination, in order to develop a long-term market scenario for CSP/desalination.

The maturity of point concentrating systems is not as high as that of line concentrating systems. In spite of first demonstration projects were of central receivers type (in Europe in the 1970ies), the only commercial CSP plants today are line concentrating parabolic trough systems. It is still uncertain whether central receivers will be able to compete with line concentrating systems in the lower temperature range up to 550 °C for steam generation. Up to now, line concentrating systems have had clear advantages due to lower cost, less material demand, simpler construction and higher efficiency, and there is still no evidence of a future change of that paradigm [6].

On the other hand, neither parabolic troughs nor linear Fresnel systems can be used to power gas turbines. In the high-temperature range up to 1000 °C and more, central receivers are the only available option to provide solar heat for gas turbines and combined cycle systems. However, it is still uncertain

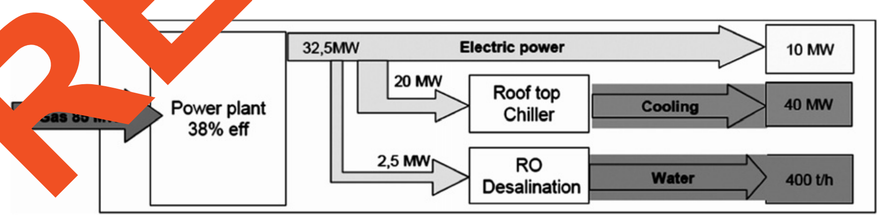


Fig. 21. Conventional solution for power, cooling and water for a hotel resort in Aqaba [6].

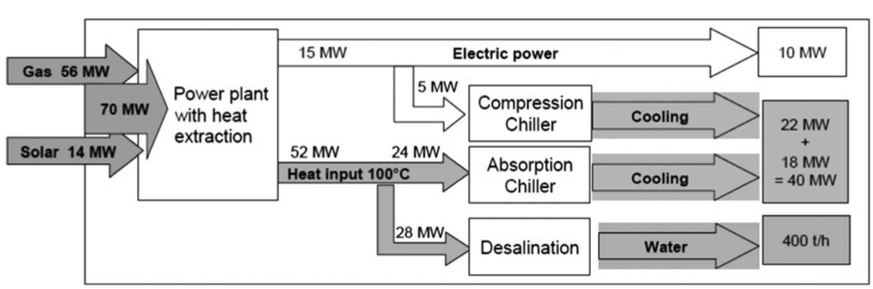


Fig. 22. Integrated solution for power, cooling and water supported by CSP [6].

Table 12
Characteristics of current concentrating solar power technologies [6].

Concentration Method	Line concentrating system		Point concentrating system	
Solar field type	Parabolic trough	Linear fresnel	Central receiver	Parabolic dish
State of the Art	commercial	precommercial	demonstrated	demonstrated
Cost of solar field (€/m^2)	200–250	150–200	250–300	> 350
Typical unit size (MW)	5–200	1–200	10–100	0.010
Construction requirements	demanding	simple	demanding	moderate
Operating temperature	390–550	270–550	550–1000	800–900
Heat transfer fluid	synthetic oil, water/steam	synthetic oil, water/steam	air, molten salt, water/steam	air
Thermodynamic power cycle	Rankine	Rankine	Brayton, Rankine	Stirling, Brayton
Power Unit	steam turbine	steam turbine	gas turbine, steam turbine	Stirling engine
Experience	high	low	moderate	moderate
Reliability	high	unknown	moderate	high
Thermal storage media	molten salt, concrete, PCM	molten salt, concrete, PCM	molten salt, ceramics, PCM	molten salt, ceramics, PCM
Combination with Desalination	simple	simple	simple	simple
Integration to the Environment	difficult	simple	moderate	Moderate
Operation requirements	demanding	simple	demanding	Simple
Land Requirement	high	low	high	Moderate

Table 13
Cost of concentrated solar–thermal–electric technologies [11,12].

Specification/type	Solar dish–engine	Parabolic trough	Solar power tower
Standard plant size, MW	2.5-100	100	100
Max efficiency, %	30	24	22
Specific power, W/m^2	200	300	300
Basic plant cost, $/W	2.65	3.22	3.62
Total US installation, MW	0.118	354	10
Largest unit in the USA, MW	0.025	80	10
Demonstrated system, h	80,000	300,000	2000

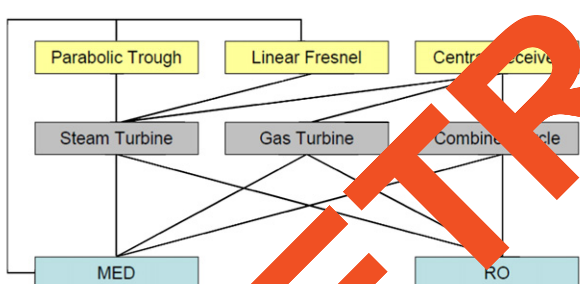


Fig. 23. Options of combining concentrating solar power (CSP) with desalination technologies [5,6].

whether the technical challenges involved with such systems will be solved satisfactorily and if large scale units will be commercially available in the medium term future. The early stage of development of those systems still leaves open questions with respect to cost, reliability and scalability for mass production at large scale, although their feasibility has been successfully demonstrated. Therefore, central receiver systems have been discarded from being used as reference CSP technology for this study, although this does not exclude the possibility that they may have an important role in a future competitive market of CSP systems for electricity and desalination [6].

As the main scope of the study was to assess the potential of large scale desalination units with CSP for the major centers of demand in KSA, parabolic dish systems can be excluded as well, as they only operate in the kilowatt range. However, they could be applied for decentralized, remote desalination. The exclusion of point concentrating systems leaves parabolic trough and linear Fresnel concentrators as major candidates for a CSP reference technology. Looking at Tables 12 and 13, Fresnel beats the parabolic trough in most items except for two: 1-current experience with parabolic trough technology is by far more extended than that with linear Fresnel systems and, 2- as a consequence, a comparison of reliability with the highly reliable parabolic trough cannot yet be made.

However, looking at the long-term perspective of CSP, it must be noted that the linear Fresnel has many advantages, ranging from lower cost and lower material requirements to a much simpler construction and a much better integration to the environment. In fact, linear Fresnel systems can be considered as next generation parabolic troughs, if they proof to be technically reliable. Linear Fresnel systems differ from parabolic troughs only in terms of optical performance and mechanical operation of the sun-tracking mirrors. All other components, from the heat transfer circuit to the steam power cycle, are in principle the same as in equivalent parabolic trough plants. This allows to transfer part of the existing experience, which is related to those components, from parabolic trough to linear Fresnel systems [4–6].

Taking into consideration the specific advantages of Fresnel systems in relation to seawater desalination, and also the experience with the Aqaba Solar Water project, linear Fresnel technology can be chosen as reference for CSP technology [6]. This is for more in-depth analysis of a combination with seawater desalination and for long-term scenario evaluations within this study. This does not exclude any other CSP technology from being considered, assessed or used in combination with seawater desalination, either directly by solar heat or through the generation of electricity.

9.5. Concentrating solar power for large scale seawater desalination

As shown before, concentrating solar power plants can generate electricity which can be used for membrane desalination via reverse osmosis. CSP plants can also be used for combined heat and power generation. Thus, also thermal desalination methods like multi-effect or multi-stage-flash can be coupled with and powered by CSP, either directly or in co-generation with electricity.

A major advantage of CSP for desalination can be appreciated as shown in Figs. 24–26. Modeling of equivalent wind, PV and CSP systems with 10 MW installed power capacity each at Hurghada, Egypt was done for one week of operation. It is clear that, wind and photovoltaic power systems deliver fluctuating power and either allow only for intermitting solar operation of a desalination plant or require considerable conventional backup power. A concentrating solar power plant can deliver absolutely stable and constant power capacity. This is due to its thermal energy storage capability and the possibility of hybrid operation with fuel.

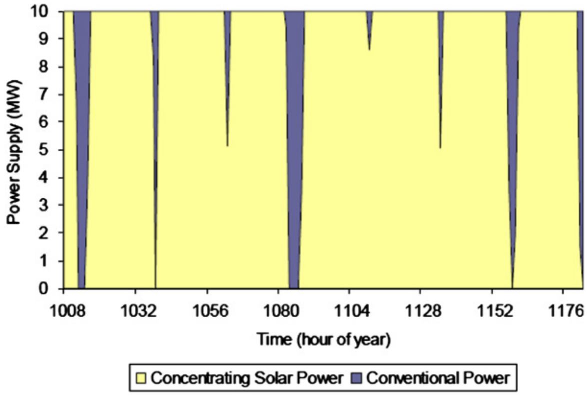


Fig. 24. Solar power provided by a modeled CSP-plant with 16 h thermal storage in a week in spring, and fuel consumed in hybrid mode from the same plant for constant 10 MW capacity.

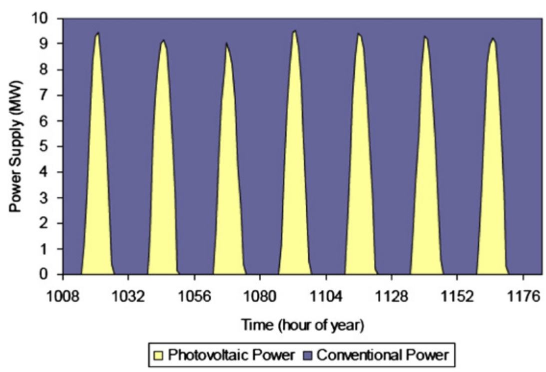


Fig. 25. Power supplied by modeled 10 MW PV capacity and conventional backup power from the grid needed to provide constant 10 MW power supply for desalination for a week in spring.

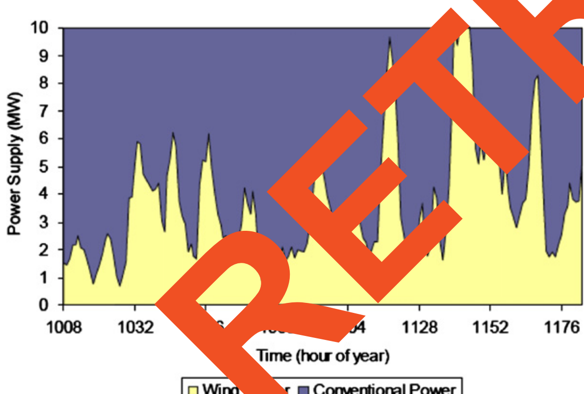


Fig. 26. Power supplied by 10 MW installed wind capacity and conventional backup power from the grid needed to provide constant 10 MW power supply for desalination for a week in spring.

In order to operate at constant power, desalination plants using wind or PV electricity would additionally need to be coupled with the electricity grid for external backup. In both cases a 10 MW conventional plant as backup capacity would have to be installed and operated almost all the time, providing a relatively small portion of electricity during daytime and wind periods and full capacity during night and wind calms. On the other hand, if intermittent operation is allowed, much higher power capacities of PV and wind power would have to be installed to produce the same amount of electricity and water. In this example the renewable share provided by CSP is 91%, that of PV is 25% and that of wind power is 37%. Depending on the conditions at different locations in MENA, these numbers can be also considered as typical for the average annual performance of such systems [6].

As a consequence, CSP plants save both fuel and installed capacity when compared to other renewable energy sources like PV and wind for desalination. Instead of conventional backup power, electricity generated by all three systems could be stored in batteries, hydro-pump or hydrogen energy storage in order to provide continuous power capacity to desalination. In that case, the additional electrical storage capacities needed by CSP would be rather small, while significant storage would be required for PV and wind power, prohibitively increasing the overall system cost.

Intermittent operation of desalination plants is possible and has already been realized in smaller systems. However, for large-scale seawater desalination plants, intermittent operation would lead to a rather low economic performance as the investment of the desalination plant would not be amortized properly, and the plant's lifetime would be reduced by increased scaling, fouling and corrosion. Overall energy consumption would increase, as temperature- and pressure would continuously change which would lead to efficiency losses within components of the plants.

In the following we will therefore concentrate on concentrating solar power as energy source for thermal and membrane desalination, and describe the technical and economic performance of large scale CSP systems for the combined generation of power and desalted seawater.

9.6. Concentrating solar power for small scale seawater desalination

An important issue for small systems is the usual up-scaling of specific system costs when downscaling the size of the collector fields. Conventional parabolic troughs or central receivers will hardly be competitive when they are scaled down to units smaller than [illegible] MW. In this market segment, CSP will have to compete with PV- and wind-powered RO-systems and with non concentrating solar thermal collector systems However, low-temperature parabolic trough and linear Fresnel systems are likely to be competitive in this market segment, as they offer low cost and a unique possibility of energy storage by hot water at temperatures below 100 °C. Considerable amounts of energy (35 kWh/m^3) can be stored in hot water in the temperature range between the maximum storage temperature of e.g. 95 °C and the operating temperature of an MED plant of e.g. 65 °C. It may be feasible to directly heat and store incoming seawater for later processing during hours without sunshine. Thus, fluctuating solar energy input would not affect continuous operation of the desalination plant. Small part of the solar collector field or a different source could be used to provide the relatively small amounts of electricity required by MED. There is a considerable market for small-scale solar systems for seawater and brackish water desalination in remote, urban and in agricultural areas. In order to apply these technologies, technical and economic feasibility must be assessed for specific sites and applications, and pilot plants must be built to demonstrate reliability of system operation

9.7. Challenges to be met when integrating solar energy and desalination plants

The following points are to be considered in integrating solar energy and desalination plants:

a- To determine the solar power supply against SWRO demand characteristics as represented in Fig. 27.
b- Act on SWRO Power consumption and follow closely the power supply curve (daily ramp up, ramp down) as plotted in Fig. 28,
c- Train shut down and restarts at least 1/day to be considered.

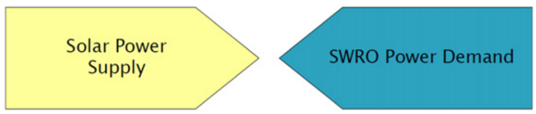


Fig. 27. Representation of matching between supply and demand [6].

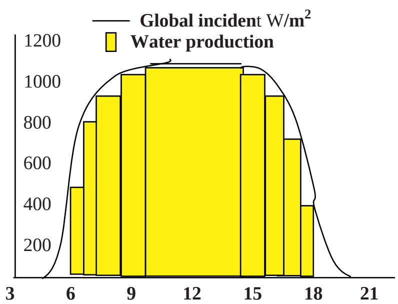


Fig. 28. SWRO Power consumption follows closely the power supply curve (summer, full sun 1000 W/m^2, 12 h full power Khafji simulation) [6].

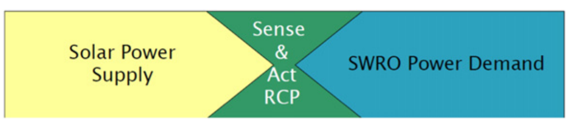


Fig. 29. Representation of using RCP to match between supply and demand.

d- Real time reaction on power variations due to dust and clouds.
e- To consider the option of extending operational hours by using grid power, through implementation of a Real time Control Program (RCP) as represented in Fig. 29.
f- Sense and Model Solar Power Availability

10. Environmental Impacts of Desalination plants [6]

Impacts of seawater desalination to the environment, which will be explained in this section, are caused by feed water intake, material and energy demand, and by brine discharge.

The selection of seawater intake system depends on the raw water source, local conditions and plant capacity. The best seawater quality can be reached by beach wells but in these cases the amount of water that can be extracted from each beach well is limited by the earth formation, and therefore the amount of water available by beach wells is very often far below the demand of the desalination plant. For small and medium reverse osmosis plants, a beach well is often used. For seawater with a depth of less than 3 m, short seawater pipes or an open intake are used for large capacities. Long seawater pipes are used for seawater with depths of more than 30 m. The seawater intake may cause losses of aquatic organisms by impingement. The effects of the construction of the intake piping result from the disturbance of the seabed which causes re-suspension of sediments, nutrients or pollutants into the water column. The extent of damage during operation depends on the location of the intake piping, the intake rate and the overall volume of intake water. Alternative techniques of feed water intake will be identified in Section 11.

The second impact category is linked to the demand of energy and materials inducing air pollution and contributing to climate change. The extent of impact through energy demand is evaluated by life cycle assessment (LCA). The impacts of this category can be mitigated effectively by replacing fossil energy supply by renewable energy and using waste heat from power generation for the thermal processes.

The third impact category comprises effects caused by the release of brine to the natural water body. On one hand the release of brine stresses the aquatic environment due to the brine's increased salinity and temperature. On the other hand the brine contains residuals of chemicals added during seawater pre-treatment and by-products formed during the treatment. These additives and their by-products can be toxic to marine organisms, and/or can accumulate in sediments. Apart from the chemical and physical impact of the brine depends on the hydrographical situation which influences brine dilution and on the biological features of the discharge site. For instance, shallow sites are less appropriate for dilution than open-sea sites and sites with abundant marine life are more sensitive than hardly populated sites. But dilution can only be a medium-term mitigation measure. In the long run the pre-treatment of the feed water must be performed in an environmentally friendly manner. Therefore alternatives to conventional chemical pre-treatment must be identified.

The environmental impacts of seawater desalination will be discussed separately for each technology because of differences in nature and magnitude of impacts. The technologies regarded here are MSF, MED and RO as they are, at least at the moment, the predominant ones of all desalination technologies and therefore these plants are responsible for almost all impacts on the environment caused by desalination. An environmental impact of MSF and RO desalination technologies is explained below:

10.1. *Multi-Stage Flash desalination (MSF)*

10.1.1. *Seawater intake*

Due to their high demand of cooling water, MSF desalination plants are characterized by a low product water conversion rate of 10–20%. Therefore the required volume of seawater input per unit of product water is large, i.e. in the case of a conversion rate of 10%, 10 m^3 of seawater are required for 1 m^3 of produced freshwater (see Fig. 30). So, combining the high demand of seawater input and large size of MSF plant, the risks of impingement and entrainment at the seawater intake site must be regarded as high. Therefore, the seawater intake must be designed in a way that the environmental impact is low.

10.1.2. *Discharge of brine containing additives*

The discharge of brine represents a strong impact to the environment due to its changed physical properties, i.e. salinity, temperature and density, and to the residues of chemical additives or corrosion products. In MSF plants common chemical additives are biocides, anti-scales, antifoaming agents, and corrosion inhibitors. The conditioning of permeate to gain palatable, stable drinking water requires the addition of chlorine for

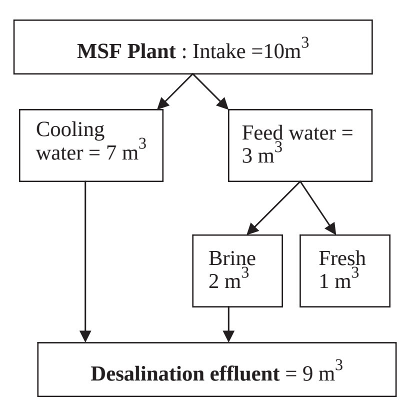


Fig. 30. Flow chart of reference MSF process (mass balance) [6].

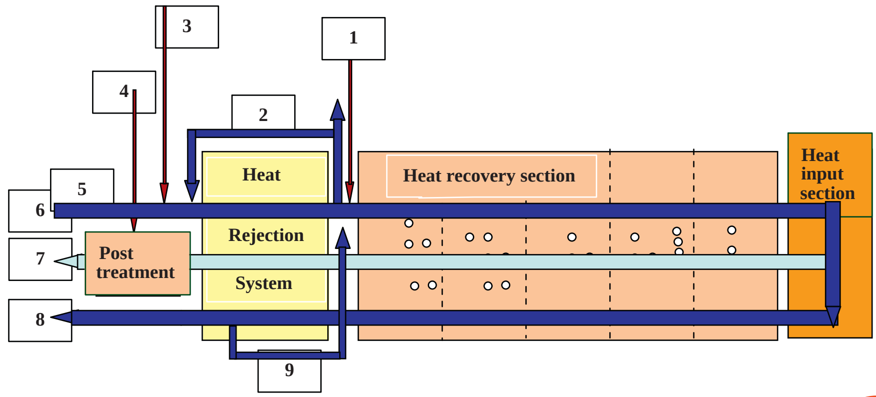


Fig. 31. MSF process scheme with input and output concentrations of additives and brine characteristics [6].

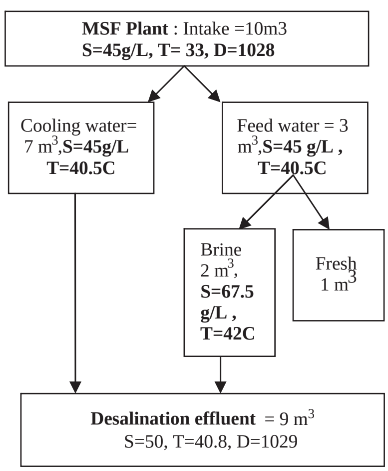


Fig. 32. Flow chart of reference MSF process with salinity (*S*, in g/L), temperature (*T*, in °C) and density (*D*, in g/L).

disinfection, calcium, e.g. in form of calcium hydroxide for re-mineralization and pH adjustment.

In case of acidification as pretreatment removal of boron might be necessary. Fig. 31 shows where the chemicals are added, and indicate the concentrations as well as the characteristics of the brine and its chemical load.

10.1.3. Physical properties of brine

The physical parameters of the brine are different compared to the intake seawater. During the distillation process the temperature rises and salt accumulates in the brine. Taking the reference process (Fig. 30) with a conversion rate of approx. 10% (related to the seawater flow). As example the salinity of the brine rises from 45 g/L to 67.5 g/L (Fig. 32). Brine and cooling water temperature rises by 9 and 7.5 °C, respectively. Salinity of the brine is reduced by blending with cooling water, but still reaches a value of 5.4 g/L above ambient level. The resulting increase of density is small what can be attributed to balancing effects of temperature and salinity rise.

In general, the increase of the seawater salinity in the sea caused by solar evaporation is normally much higher than by desalination processes. However, the brine discharge system must be designed in a way that the brine is well distributed and locally high temperature and salinity values are avoided.

10.1.4. Biocides

Surface water contains organic matter, which comprises living or dead particulate material and dissolved molecules, leads to biological growth and causes formation of bio-film within the plant. Therefore the seawater intake flow is disinfected with the help of biocides. The most common biocide in MSF plants is chlorine. A concentration of up to 2000 μg/L in the seawater intake flow is sustained by a continuous dosage. Chlorine reacts to hypochlorite and, in the case of seawater, mainly to hypo-bromide. Residual chlorine is released to the environment with the effluents from cooling and distillation where it reaches values of 200–500 μg/l, representing 10–25% of the dosing concentration. Assuming a product-effluent-ratio of 1:9 the specific discharge load of residual chlorine per m^3 of product water is 1.8–4.5 g/m^3. For a plant with a desalination capacity of 24,000 m^3/day, for instance, this means a release of 43.2–108 kg of residual chlorine per day.

Further degradation of available chlorine after the release to the water body will lead to concentrations of 20–50 μg/L at the discharge site. Chlorine has effects on the aquatic environment because of its high toxicity, which is expressed by the very low value of long-term water quality criterion in seawater of 7.5 μg/L recommended by the U.S. Environmental Protection Agency(EPA) and the predicted no effect concentration (PNEC) for saltwater species of 0.04 μg/L determined by the EU environmental risk assessment.

Another aspect of chlorination is the formation of halogenated volatile liquid hydrocarbons. An important species is bromoform, a tri-halo-methane volatile liquid hydrocarbon. Concentrations of up to 10 μg/l of bromoform have been measured near the outlet of the Kuwaiti MSF plant Doha West. The toxicity of bromoform has been proven by an experiment with oysters which have been exposed to a bromoform concentration of 25 μg/L and showed an increased respiration rate and a reduced feeding rate and size of gonads. Larval oysters are even more sensitive to bromoform, as significant mortality is caused by a concentration of 0.05–10 μg/l and acute, 48 h exposures.

10.1.5. Anti-scalants

A major problem of MSF plants is the scale formation on the heat exchanger surfaces which impairs heat transfer. The most common scale is formed by precipitating calcium carbonates due to increased temperatures and brine concentration. Other scale forming species are magnesium hydroxide and calcium sulphate, which are very difficult to remove as it forms hard scales. Therefore sulphate scaling is avoided in the first place by regulating the operation parameters temperature and concentration in such a way that the saturation point of calcium sulphate is not reached. Calcium carbonates and magnesium hydroxides, again, are chemically controlled by adding acids and/or antiscalants.

In the past, acid treatment was commonly employed. With the help of acids, the pH (acidity value) of the feed water is lowered to 2 or 3 and hereby the bicarbonate and carbonate ions chemically

react to carbon dioxide which is released in a de-carbonator. Thus, the $CaCO_3$ scale forming ions are removed from the feed water. After acid treatment the pH of the seawater is readjusted.

Commonly used acids are sulfuric acid and hydrochloric acid, though the first is preferred because of economic reasons. High concentrations and therefore large amounts of acids are necessary for the stoichiometric reaction of the acid. Negative effects of using acids are the increased corrosion of the construction materials and thus reduced lifetimes of the distillers. These negative effects have led to the development of alternatives: Nowadays antiscalants are replacing acids during operation. An antiscalant can suppress scale formation with very low dosages, typically below 10 ppm.

A MSF plant with a daily capacity of 24,000 m^3 releases about 144 kg of antiscalants per day if a dosage concentration of 2 mg per liter feedwater is assumed. This represents a release of 6 g per cubic meter of product water [6].

10.1.6. *Antifoaming agents*

Seawater contains dissolved organics that accumulate in the surface layer and are responsible for foaming. The use of anti-foaming agents is necessary in MSF plants, because a surface film and foam -increase the risk of salt carry-over and contamination of the distillate.

Under the assumption of a product-feedwater-ratio of 1:3 and 0.035–0.15 ppm dosing 0.1–0.45 g

per cubic meter of product water are released [6].

10.1.7. *Corrosion inhibitors and corrosion products*

An important issue for MSF plants is the inhibition of corrosion of the metals the heat exchangers are made of. The corrosive seawater, high process temperatures, residual chlorine concentrations and corrosive gases are the reason for this problem. Corrosion is controlled by the use of corrosion resistant materials, by deaeration of the feed water, and sometimes by addition of corrosion inhibitors. Especially during acidic cleaning corrosion control by use of corrosion inhibitors is essential for copper-based tubing.

The most important representative of heavy metals dissolved from the tubing material is copper, because copper-nickel heat exchangers are widely used. In brines of MSF plants it represents a major contaminant. Assuming a copper level of 15 ppb in the brine and a product-brine-ratio of 1:2, the resulting output from the reference MSF plant with a capacity of 24,000 m^3/d is 720 g copper per day [6].

10.2. *Multi-Effect Desalination (MED)*

10.2.1. *Seawater intake*

The flow rate of the cooling water which is discharged at the outlet of the final condenser depends on the design of the MED distiller and the operating conditions. In the case of a conversion rate of 11% (related to the seawater intake flow), 9 m^3 of seawater are required for 1 m^3 of fresh water (Fig. 33). It was highlighted that the potential damage caused by impingement and entrainment at the seawater intake must be regarded as high [6].

10.2.2. *Discharge of brine containing additives*

The discharge of brine represents a strong impact to the environment due to its changed physical properties and to the residues of chemical additives or corrosion products. In MED plants common chemical additives are biocides, antiscalants, antifoaming agents at some plants, and corrosion inhibitors at some plants. The conditioning of permeate to gain palatable, stable drinking water requires the addition of chlorine for disinfection, calcium, e.g. in form of calcium hydroxide, for re-mineralization and pH adjustment. (Fig. 35) shows where the chemicals are added and at which concentrations as well as the characteristics of the brine and its chemical load.

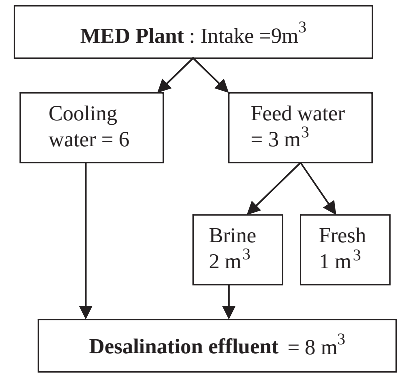


Fig. 33. Flow chart of reference MED process.

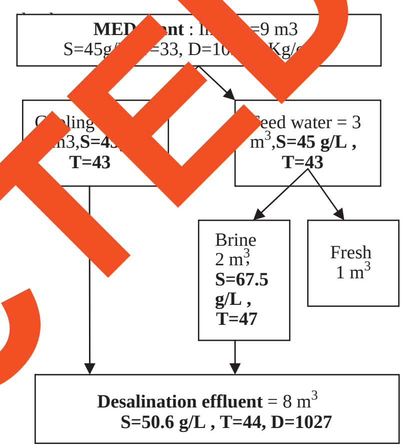


Fig. 34. Flow chart of reference MED process with salinity (*S*, in g/l), temperature (*T*, in °C) and density (*D*, in g/l),, modified biocides.

10.2.3. *Physical properties of brine*

The physical parameters of the brine are different compared to the intake seawater. During the distillation process the temperature rises and salt accumulates in the brine. Taking the reference process (Fig. 33) with a conversion rate of approx. 11.2% as example the salinity rises from 45 g/L to 66 g/L (Fig. 34). Brine and cooling water temperature rises by about 14 and 10 C, respectively. Salinity of the brine is reduced by blending with cooling water, but still reaches a value of 5.6 g/L above ambient level. The resulting decrease of density is very small what can be attributed to balancing effects of temperature and salinity rise.

Assuming a product-effluent-ratio of 1:8 the specific discharge load of residual chlorine per m^3 of product water is 1.6–4.0 g/m^3. For a plant with a daily desalination capacity of 24,000 m^3, for instance, this means a release of 38.4–96.0 kg of residual chlorine per day [6].

10.2.4. *Antiscalants*

A major problem of MED plants is the scale formation on the heat exchanger surfaces which impairs the heat transfer. The most common scale is formed by precipitating calcium carbonates due to increased temperatures and brine concentration.

A MED plant with a daily capacity of 24,000 m^3 releases about 144–288 kg of antiscalants per day if a dosage concentration of 2–4 mg per liter feedwater is assumed. This represents a release of 6 g per cubic meter of product water [6].

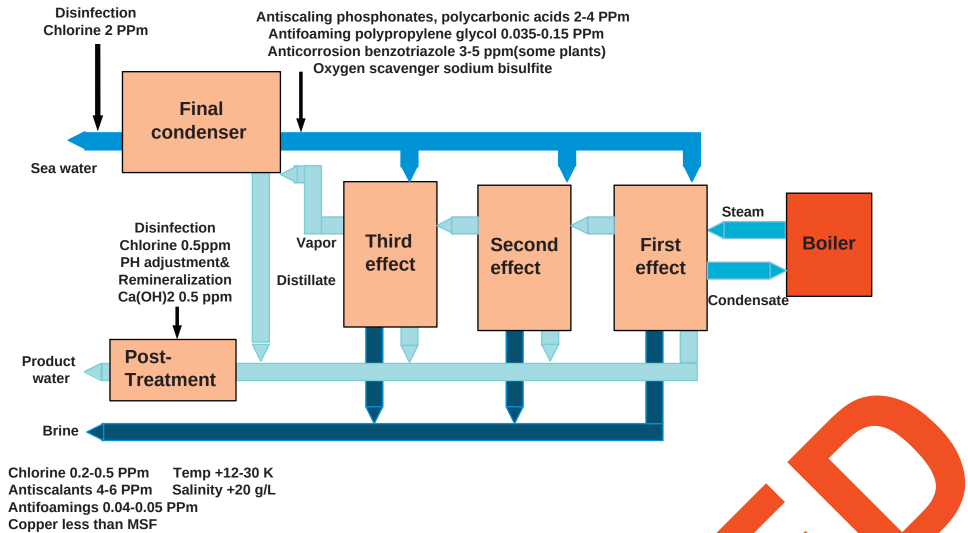


Fig. 35. MED process scheme with input and output concentrations of additives an[illegible]ine ch[illegible]teristics.

10.2.5. Antifoaming agents

MED plants also use antifoaming agents, but compared to MSF plants, it is less consumer.

Under the assumption of a product-feedwater-ratio of 1:3 and 0.035-0.15 ppm dosing 0.1–0.45 g per cubic meter of product water are released.

10.2.6. Corrosion inhibitors and corrosion products

The corrosion inhibitors that are used in MSF plants are als[illegible] necessary in MED plants. However, it is assumed that the coppe[illegible] load is smaller compared to MSF plants as operation temperatures are lower and piping material with lower copper con[illegible]s are used, such as titanium and aluminum-brass.

10.3. Reverse Osmosis (RO)

10.3.1. Seawater intake

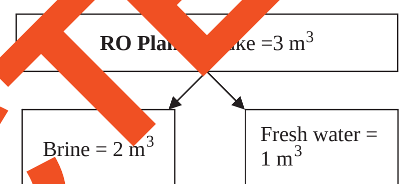
The conversion rate of RO processes ra[illegible]s [illegible]een 20 an[illegible]0%, S0, an intake volume of less than 5 m^3 [illegible] seawater [illegible] cubic meter of freshwater is enough. Therefore, co[illegible]red to the the[illegible]l processes the mechanical process of RO req[illegible]es sig[illegible]cantly less intake water for the same amount of produ[illegible]at[illegible] Consequently the loss of organisms through impingement an[illegible]rainm[illegible] is lower. The flow chart shown in (Fig. 36) [illegible] on a [illegible]on rate of 33%.

10.3.1.1. Discharge o[illegible]ine [illegible] additives. The discharge of brine represents a stro[illegible]mpact to the environment due to its changed physical propertie[illegible] to the residues of chemical additives or corrosion products. In RO p[illegible]nts common chemical additives are biocides, acids(if used), antiscalants, coagulants, and, in the case of polyamide membranes, chlorine deactivators. The conditioning of permeate to gain palatable, stable drinking water requires the addition of chlorine for disinfection, calcium, e.g. in form of calcium hydroxide, for re-mineralization and pH adjustment.

(Fig. 37) shows where the chemicals that are added and at which concentrations as well as the characteristics of the brine and its chemical load.

10.3.2. Physical Properties of Brine

The salinity of the brine is increased significantly due to high conversion rates of 30 to 45%. The conversion rate of 32% of the process presented in Figs. 6–9 leads to a brine salinity of 66.2 g/l (Fig. 38). As the temperature stays the same during the whole process, also density increases significantly from 1028 g/L to



[illegible] 36. Flow chart of reference RO process.

[illegible]/L. If the RO process is coupled with electricity generation a[illegible] th[illegible]ffluent streams are blended, the warmed cooling water [illegible]om the power plant reduces the overall density slightly com[illegible]ared to the ambient value and the overall salinity is almost [illegible]educed to the ambient level.

10.3.3. Biocides

Surface water contains organic matter, which comprises living or dead particulate material and dissolved molecules, leads to biological growth and causes formation of biofilm within the plant. Therefore the RO feed water is disinfected with the help of biocides. The most common biocide in RO plants is chlorine. A concentration of up to 1000 µg/l is sustained by a continuous dosage. Chloride reacts to hypochlorite and, in the case of seawater, especially to hypobromite. In RO desalination plants operating with polyamide membranes de-chlorination is necessary to prevent membrane oxidation. Therefore the issue of chlorine discharge is restricted to the smaller portion 0of plants which use cellulose acetate membranes. Regarding these plants residual chlorine is released to the environment with the effluents where it reaches values of 100–250 µg/l, representing 10–25% of the dosing concentration. Assuming a product-effluent-ratio of 1:2 the specific discharge load of residual chlorine per m^3 of product water is 0.2–0.5 g/m^3. For a plant with a daily desalination capacity of 24,000 m^3, for instance, this means a release of 4.8–12 kg of residual chlorine per day. Again, the problem of chlorine discharge is restricted to plants with cellulose acetate membranes. In contrast, the release of chlorination by-products is an issue at all RO plants regardless of the material of their membranes, as by-products form up to the point of de-chlorination. The effects of chlorine are described above [6].

10.3.4. Coagulants

The removal of suspended solids is essential for a good membrane performance. For this purpose coagulants and poly-electrolytes are added for coagulation–flocculation and the resulting flocs are hold back by dual media sand–anthracite filters.

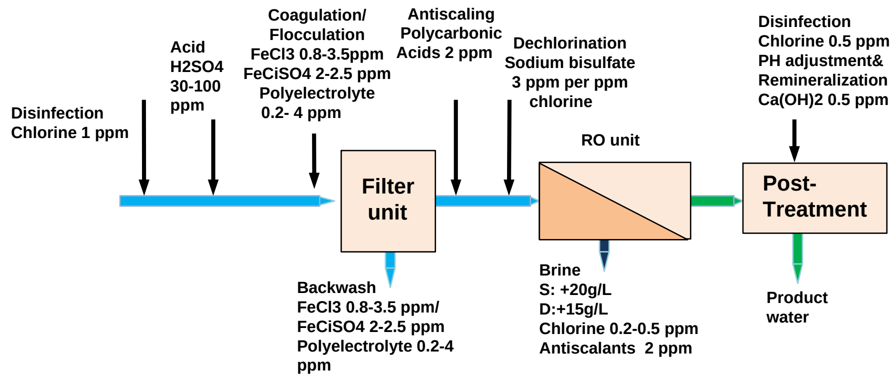


Fig. 37. RO process scheme with input and output concentrations of additives and brine characteristics, modified.

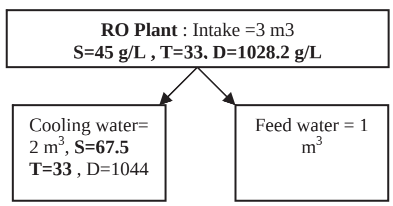


Fig. 38. Flow chart of reference RO process with salinity (*S*, in g/l), temperature (*T*, in °C) and density (*D*, in g/l), modified.

Fig. 39. Red brines containing ferric sulphate from filter backwash at Ashkelon RO desalination plant; backwash with 63,000 m³ 10–15 min every hour [6,7].

Coagulant substances are ferric chloride, ferrous sulphate, and ferric chloride sulphate or aluminum chloride. To sustain the efficiency of the filters, they are backwashed regularly.

Common practice is to discharge the backwash brines to the sea. This may affect marine life as the brines are colored by the coagulants and carry the flocs (see Fig. 39). The dosage is proportional to the natural water turbidity and can be high as 30 mg/l. This extreme dosage results in a specific load of 90 g per m^3 of product water and a daily load of a 24,000 m^3/d plant of 2200 kg which adds to the natural turbidity [6].

Polyelectrolytes support the flocculation process by connecting the colloids. Possible substances are polyphosphates or polyacrylic acids and polyacrylamides respectively, which are also used as antiscalants. A dosage of 500 μg/l implies a discharge of 1.5 g per m^3 of product water and a daily load of a 24,000 m^3/d plant of 36 kg which adds to the natural turbidity [6].

10.3.5. Antiscalants

The main scale forming species in RO plants are calcium carbonate, calcium sulphate and barium sulphate. Acid treatment and antiscalant dosage are used for scale control. Here, sulphuric acid is most commonly used and dosed with a range of 30–100 mg/L. During normal operation the alternative use of antiscalants, such as polyphosphates, phosphonates or polycarbonic acids, has become very common in RO plants due to the negative effects of inorganic acid treatment explained above. As practice low concentrations of about 2 mg/l are sufficient.

A RO plant with a daily capacity of 24,000 m^3 releases about 144 kg of antiscalants per day if dosage concentration of 2 mg per -litre feed water and a product-feedwater-ratio of 1:3 are assumed. This represents a release of 6 g per cubic meter of product water.

10.3.6. Membrane cleaning agents

Apart from acid cleaning, which is carried out with citric acid or hydrochloric acid, membranes are additionally treated with sodium hydroxide, detergents and complex-forming species to remove biofilms and silt deposits. By adding sodium hydroxide, the pH is raised to about 12 where the removal of biofilms and silt deposits is achieved. Alkaline cleaning solutions should be neutralized before discharge

10.3.7. Corrosion products

In RO plants corrosion is a minor problem because stainless steels and non-metal equipment predominate. There are traces of iron, nickel, chromium and molybdenum being released to the water body, but they do not reach critical levels. Nevertheless, an environmentally sound process should not discharge heavy metals at all; therefore alternatives to commonly used material need to be found.

10.3.8. De-chlorination

The removal of chlorine is performed with sodium bisulfite, which is continuously added to reach a concentration three to four times higher than the chlorine concentration (1500–4000 μg/L). The corresponding amount per cubic meter of product water is 4.5–12 g/m^3. As this substance is a biocide itself and harms marine life through depletion of oxygen, overdosing should be prevented. Alternatively sodium metabisulfite is used [6,7].

11. Options for Environmentally Enhanced Seawater Desalination

This section is directed to describe how the future of desalination plants could be optimized for minimum environmental impact. By using heat and electricity from concentrating solar power plants the major impacts from energy consumption and air pollution are avoided. Enhancing the practice of seawater intake and hereby achieving higher quality input seawater leads to less chemical intensive or even chemical-free pre-treatment and consequently less potential waste products in the effluents. The

pre-treatment process itself can be advanced to further reduce the use of chemicals. Finally the practice of discharge needs to be improved in such a way that optimum dilution is guaranteed. Among the market-dominating desalination technologies, MSF performs worst regarding efficiency, costs and overall impact, which is why it falls out of consideration. Therefore future concepts will only be illustrated for MED and RO.

11.1. Enhanced CSP/MED plant

The future advanced MED plant would run completely with heat and electricity from concentrating solar power (CSP/MED). The impacts from energy consumption are reduced to a minimum originating from the upstream processes of the CSP plant, i.e. production and installation of collector field, heat storage and conventional steam power station. The related emission can only be reduced by increasing the renewable share of power generation of the total energy economy. During operation of the plant there is no use of fossil energy carriers and there are no emissions to the atmosphere. The features characterizing the future MED plant are summarized schematically in Fig. 40 and are presented in the following.

The seawater intake is designed as a seabed filter intake through directed drilled horizontal drains. This system is environmentally compliant, because it does not affect aquatic organisms neither through impingement nor through entrainment. Where this system cannot be realized, beach wells are the suggested alternative. Open source water intake is considered only on sites where neither horizontal seabed filters nor beach wells are possible. Due to the filtrating effect of seabed intake the source water is largely free from suspended inorganic and organic matter.

Optimally, the pre-filtered seawater does not require chlorination due to the long passage through the subsoil. In that case the pre-treatment consists of a nano-filtration system to eliminate colloids, viruses and hardness. As these ions are largely removed no anti-scalants are necessary. Furthermore anti-foaming is dispensable as hardly any organic matter passes the nano-filtration membrane. The nano-filtration system comprises a permeate buffer tank where the NF permeate is stored for membrane backwashing. Backwashing is the essential measure to retain the performance of the NF membrane and has to be done regularly with a sufficient backwash flow rate. The backwash brine is blended with the distillation brine.

In case of sub-optimally pre-filtered source water and unfiltered open source water, further pretreatment steps consisting of micro-filtration and ultra-filtration become necessary each with a backwashing facility. The tubing is made of corrosion-resistant material, such as titanium, or of conventional material coated with a durable protection film respectively. Anyway, the risk of corroding tubes is reduced by the enhanced pre treatment that does not require acid cleaning anymore. However, to guarantee effluents free from heavy metals a post-treatment step can be inserted optionally where the heavy metals are removed applying one of the techniques described above.

The practice of effluent discharge is enhanced with a diffuser system providing optimal and rapid dilution. In the future advanced CSP/MED plant, the use of chemicals and the concentration of brine will be avoided to a great extent by increased filtering and diffusion. Additional energy for this process will be obtained from solar energy. For a first estimate, it is assumed that the chemicals required per cubic meter of desalted water will be reduced to about 1% of present amounts and that on the other hand an additional 40% of electricity will be required for pumping.

11.2. Enhanced CSP/RO Plant

A future advanced RO plant would run completely with electricity from concentrating solar power plants. During operation there is no use of fossil energy carriers and consequently no emissions to the atmosphere. The features characterizing the future RO plant are summarized schematically in Fig. 41 and are presented in the following.

The seawater intake is designed as a seabed filter intake through directed drilled horizontal drains. Where this system cannot be realized, beach wells are the suggested alternative. Open source water intake is considered only on sites where neither horizontal seabed filters nor beach wells are possible.

Optimally the pre-filtered seawater does not necessitate chlorination due to the long passage through the subsoil. In that case the pre-treatment consists of a nano-filtration system to eliminate colloids, viruses and hardness. As these ions are largely removed no antiscalants are necessary. The nano-filtration system comprises a permeate buffer tank where the NF permeate is stored for membrane backwashing. Backwashing is the essential measure to retain the performance of the NF membrane and has to be done regularly with a sufficient backwash flow rate. The backwash brine is blended with the RO brine.

In case of sub-optimally pre-filtered source water and unfiltered open source water further pretreatment steps consisting of micro-filtration and ultra-filtration become necessary each with a backwashing facility. Using of NF systems before RO membranes, the number of RO stages can potentially be decreased thus reducing the investment costs and energy consumption of the RO. In analogy to the NF system, the RO unit requires a backwashing facility including

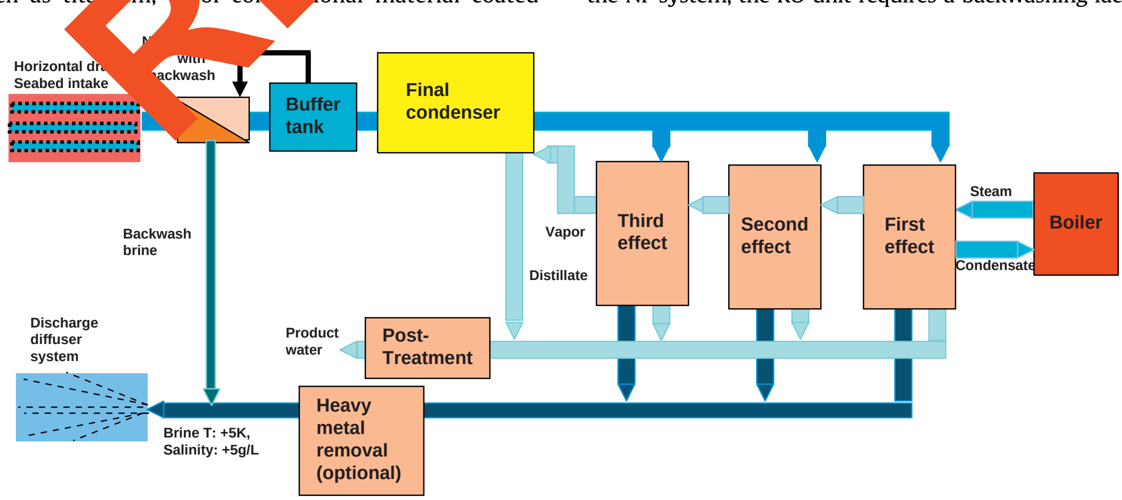


Fig. 40. Scheme of A-MED process including horizontal drain seabed intake, nano-filtration unit, buffer tank for backwash of nano-filtration membranes and discharge diffuser system.

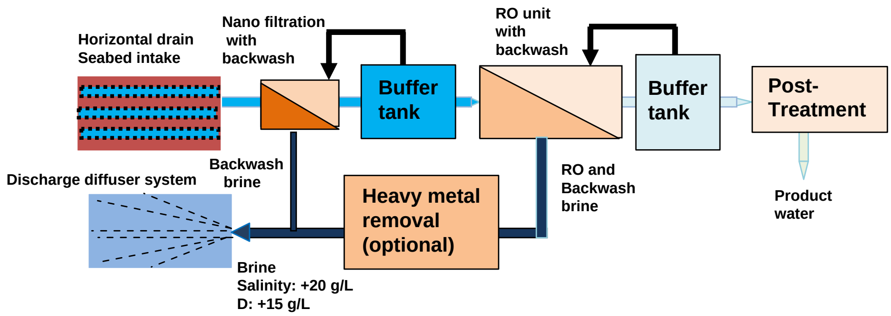


Fig. 41. Scheme of RO process including horizontal drain seabed intake, nano-filtration unit, buffer tank for backwash of nano-filtration membranes and discharge diffuser system.

a RO permeate buffer tank. The piping is made of corrosion-resistant material, such as stainless steel and PVC for high and low pressure piping respectively. Anyway, the risk of corroding tubes is reduced by the enhanced pre-treatment that does not require acid cleaning anymore. However, to guarantee effluents free from heavy metals a post-treatment step can be inserted optionally where the heavy metals are removed applying one of the techniques described above,

The practice of effluent discharge is enhanced with a diffuser system providing optimal and rapid dilution. In the future advanced CSP/RO plant, the use of chemicals and the concentration of brines will be avoided to a great extent by increased filtering and diffusion, and energy input will be delivered by solar energy.

12. Selection of Reference Plant Configuration

Seven options have been discussed including advantages and disadvantages of each one in Appendix A1. The options listed are given below:

Option-1: Central Receiver with Combined Cycle
Option-2: Central Receiver with Gas Turbine
Option-3: Central Receiver with Steam Turbine
Option-4: Linear Fresnel with Steam Turbine
Option-5: Linear Fresnel for Direct Heat
Option-6: Parabolic Trough with Steam Turbine
Option-7: Parabolic Trough for Direct Heat

13. Applications of Solar energy desalination plants, in KSA [6,14,[illegible]1]

A brief description of solar projects executed in Saudi Arabia are listed in Appendix A2. After two decades from operation, the performance results and lessons learned through operation and maintenance of selected projects were discussed and reported by Alawaji, S.H [14]. All projects are divided into the following categories:

1- PV power plant (The Solar Village Project)
2- Solar-Powered Water Desalination Projects
3- The Solar Thermal Dish Project coupled with Stirling engines to convert the collected solar thermal energy into mechanical energy.
4- The 350 kW Solar Hydrogen Production Project (solar-powered hydrogen-generation plant).
5- The Solar-Powered Hydrogen Utilization Project using an internal combustion engine enabled it to use hydrogen as a fuel instead of petrol or gasoline.
6- The Solar-Powered Highway Devices Project (lightning)
7- Solar dryers (drying dates by solar energy)
8- The Solar Water Heating Project
9- The Solar Energy Education and Training Project.

The performance results and lessons learned from each one are summarized in the following subsections [6]

13.1. *The solar village project (solar power plant)*

The project aims to use solar energy to supply power for remote villages that are not served by an electric power grid. The project was designed during the late seventies and started operation in the early eighties. The entire photovoltaic (PV) project site occupies an area of approximately 67,180 m^2. This computerized 350 kW concentrator PV electricity-generating power station includes 160 PV arrays (covering an area of 4000 m^2), with a total (direct current) peak output of 350 kW, with 1100 kWh lead acid battery storage, 300 kVA inverter, and a solar-powered weather-data monitoring station. The system is capable of completely automatic operation and is designed with both stand-alone and co-generation.modes of operation

Table 14 shows a summary of the 350 kW concentrator-type PV power system (PVPS).

In conclusion, the following lessons have been learned:

(i) The concentrator-type photovoltaic power system is not the best option because it needs tracking systems to follow the sun. The tracking equipment necessarily makes the system sophisticated, which then requires intensive observation and maintenance. Consequently, the overall operation and maintenance costs become higher compared with the flat type.
(ii) In a dusty environment with low rainfall, such as the Solar Village, it is necessary to carry out regular cleaning of the solar panels in order to maintain the output power of the system at an acceptable level.
(iii) Large-scale PV systems are not economically viable when operated as standalone systems to provide energy for remote sites, due to the high cost of energy storage for use when there is no sun. However, these systems can be cost-effective if they are linked directly to the grid.
(iv) A system on this scale requires continuous monitoring and observation to avoid system failure via the failure of some minor components.

13.2. *The solar-powered water desalination projects*

The first PV-powered water pumping and desalination plant was installed in 1994 at Sadus Village, approximately 70 km from Riyadh. As shown in Fig. 42, the plant consists of two separate PV fields: one (980 W_p) is used to energize a 0.55 kW submersible pump for pumping water from a well. The other (10.08 kW_p) is

Table 14
The diesel generators are no longer in existence and the space is being utilized for the installation of an electrolyzer for the production of hydrogen, using the power from the PV system Solar village performance: PV power plant—major elements [14].

PV-array field	**160 concentrator arrays (12.1 m × 2.7 m) with 64 parallel strings of 640 cells in series; 40,940 circular silicon cells (5.7 cm diameter); 160 sun-tracking electronic and drive mechanisms; Fresnel lenses (quad) and plastic housing**
PV-array cooling	**Passive**
Environment	**Desert climate: 15–45 °C ambient air temperature**
Battery	**Four lead-acid batteries (each with 120 cells in series); rated capacity of 1.6 MWh (each cell 1700 Ah)**
Battery auxiliary charger	**60 kW, 300 V (DC), 200 A for off-line maintenance**
Inverter	**300 kVA, 480 vac three-phase**
Diesel generator	**1 MW (four 250 kW units)**
Transformers	**3 MVA (two 1500 kVA units); 480–13,800 vac**
Switch gear	**600 V (DC), 480 vac and 110 vac**
Control equipment	**Manual/automatic operation with HP 9845 computer**
Uninterruptible power supply(UPS)	**10 kVA, 110 vac inverters (two units) and a 10 kW power supply at 300 V (DC)**
Instrumentation and data magnetic tape, recording equipment	**Hp 9845 computer and Hp 3052 data acquisition system**
Array for cleaning equipment	**Purified water sprays (82 °C at 100 PSI): 7.51 m (one truck mount)**

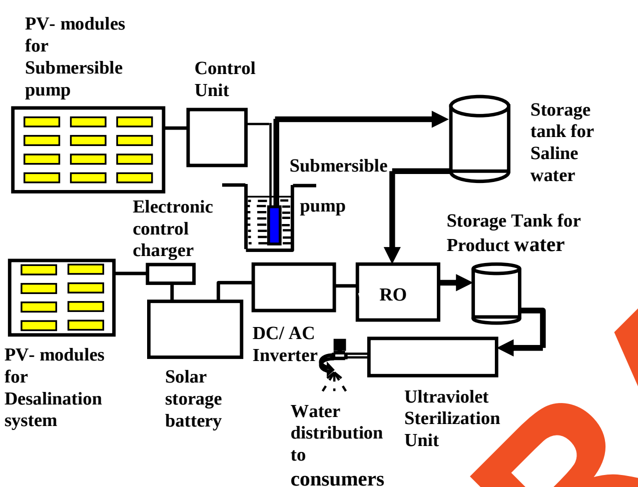


Fig. 42. General layout of actual PV water pumping and desalination plant [26].

used to supply power for a reverse osmosis unit (ROU), and to other accessories and equipment. Out of this PV installation, six PV arrays, each with adjustable tilt angle, are used to charge two parallel battery banks (with a total of 120 batteries). These batteries are then used to power the ROU, the ventilation fans, and other small loads. The ROU produces 600 L/h of potable water, from saline water of total dissolved solids of 7000 ppm [26]. The potable water is stored in a tank, which is then used by the inhabitants of the village. Table 15 gives a summary of the specifications of the design for PV-powered brackish water pumping and water desalination systems. One can summarize the lessons learned here:

(i) In remote areas, and as it is concluded from the operation of this plant, PV systems are proven to be technically and economically feasible for water pumping and desalination.
(ii) The initial cost of this plant was high and, consequently the production cost of water increases. However, the cost can be reduced remarkably by eliminating many of the instruments and equipment that are used in this particular plant for operation monitoring, and data recording for R&D purposes.
(iii) Although the PV system is very reliable in its operation, the overall system suffers from failure of its discrete (non-PV) elements, such as membranes fouling and failure of some hardware such as the solenoid valve, the high pressure pump, and the method of chemical pre-treatment of the feed water. Therefore, intensive monitoring is generally required in order to rectify these minor problems and avoid any interruption of the operation of the system.

13.3. The solar thermal dish project

This program aimed to produce 50 kW of electrical power from each thermal dish. It involved the development, construction, and testing of two large-scale solar concentrators, each being 7 m in diameter; and it used a large hollow reflector that tracks the sun. The units are coupled with Stirling engines to convert the collected solar thermal energy into mechanical energy that drives a 50 kW peak (AC) electrical generator. Both dishes were connected with the electric utility grid to evaluate the cogeneration mode, and in a stand-alone mode to demonstrate the system's capabilities for providing electric power to remote sites. Results from the project revealed that development of thermal dishes with a smaller diameter would be more practical for such remote applications, because of the operational and maintenance problems and cost-effectiveness [2].

13.4. The 350 kW solar hydrogen production project

Producing hydrogen by PV methods, and storing it, is an effective way of exploiting solar energy for the subsequent use at a desirable time. The Solar Hydrogen Production Plant was built at the Solar Village, Riyadh. It was considered as the world's first 350 kW solar-powered hydrogen-generation plant at the time of its inception. This plant uses the electricity (DC) being produced by the 350 kW photovoltaic field and the AC power from the grid supply through the rectifier. The electricity is used by advanced alkaline water electrolyzer (with 0.25 m^2 of electrode area and 120 cells) to produce 463 m^3 of hydrogen per day at normal pressure.

13.5. The solar-powered hydrogen utilization project

a successful experiment was initiated for modifications of an internal combustion engine to use hydrogen as a fuel instead of petrol or gasoline. A fuel cell is a good example of hydrogen utilization, as a Power-generation technology for the coming decades. They are universally applicable due to their high efficiency (75–80%), modularity and optimum environmental characteristics.

13.6. The solar-powered highway devices project

Modern highway safety standards require the deployment of lighting and warning devices that improve the motorist's ability

Table 15
Details of PV Sadous project [26].

PV water pumping system	
PV array	**2 × 7 × 70 Wp = 980 W, isc = 8.82 A, voc = 149.8 V**
Inverter	**Three-phase (DC) mode—1500 W, variable voltage and frequency (6–60 Hz) DC input: 120/20 V (DC), 12.5 A (DC)**
Submersible pump installed at 50 m	**Motor model MS-402, nominal power: 424–1990 W, pump model SP3A-10**
PV water desalination system	
PV module	**Six arrays, each with 12 series and two branches, isc = 8.82 A, Voc = 256.8 V, total = 144 × 70 Wp = 10.8 kWp**
DC system voltage	**120 V (DC)**
Storage batteries	**2 V (with 60 in series and two parallel branches); total 120 batteries each with 1101 Ah (C-100), with recombinator**
Electric charge control (ECC)	**Six units with MPP, rated power = 1800 W, input 0–12 A (DC), 40–25 V (DC), output 0–20 A (DC), 26–250 V (DC)**
Inverter	**5 kVA sine wave, 120 V (DC), 220 V (AC), 60 Hz, low and high voltage disconnect, low and high input and output current protection**
Uninterruptible power supply (UPS)	**250 VA, for reliable supply to the control circuit of the PV plant**
Reverse osmosis unit (ROU)	**600 l per hour of product water**
Equipment shelter	**7.6 m × 3.6 m × 3 m, thermally insulated walls and roof**

to avoid potential road hazards. Due to the difficulties in the utilization of electric power from the national grid for illuminating the highway networks, KACST has utilized the PV system to power highway devices in various remote locations within the country. They generate approximately 1.5 MWh of solar-derived electrical energy each day. The total budget for these projects was US$4.5 million, and the calculated production cost of electrical energy is US$0.1 per kWh. A number of stand-alone PV power systems, comprised of a PV array, battery, load and control subsystems, were installed at various locations. Valuable data about the operation and maintenance of these systems were then recorded and analyzed. One of these projects with a capacity of 57.60 kW_p has eight PV strings (sub arrays) that were automatically connected to the DC bus during the daytime and which simultaneously power up the lamps and provide charging current to the batteries.

13.7. Solar dryers

Drying immature dates is a problem for many countries where the relative humidity is high during the drying season. Drying dates by solar energy is important for reducing the overall maturation time, as well as for minimizing the quantity of dates lost during the process. The ERI, in cooperation with the Ministry of Agriculture and Water, conducted various research studies in order to develop the most efficient systems for drying dates using solar energy. Within this context, a number of solar dryers have been designed, installed and experimentally tested at the Al-Hassa and Qatif Agricultural experimental sites.

13.8. The Solar water heating project

One way to reduce electricity consumption in water-heating sectors is to introduce solar water heating systems (SWHS) for different hot water applications (for domestic and industrial use). The results and learning lessons are:

The average solar heating energy, produced per square meter of collection area is about 30 kWh per day. The calculated cost of 1 kWh of useful heating energy from solar power is around 0.13 Saudi riyal (US$ 0.035). Recently, a special metallic absorber for flat plate collectors has been designed, with a hydraulic press for bulk manufacturing. The design of the tested absorber, and other technical know-how, will be handed over to interested industries for commercialization purposes. It is reported, that a thermosyphon domestic SWHS (based on locally fabricated solar collectors with an area of 3.6 m^2) could provide sufficient hot water for a family of five persons living in Saudi Arabia and it would cost 4500 Saudi riyal (US$1200.00).This shows that the final cost of locally fabricated and environmentally tested SWHS will be about 60%cheaper than imported SWHS [illegible]. Obviously, costs will be drastically reduced with mass production. More than 1100 solar flat-plate collectors have been installed on the rooftops of 373 residences of different categories (like villas, terraced houses, and apartments) at the KACST campus at Riyadh. Each family residence is equipped with three solar flat-plate collectors (with a total surface area of 6.36 m^2) and a hot water storage tank with a capacity of 65 gallons. The total effective surface area of the solar flat-plate collector at the KACST campus is 2249 m^2, which generates about 67 MWh of useful heating energy each day.

13.9. The solar energy education and training project

Most of the developing countries fall within regions where solar energy is abundant, but it is felt that their interest regarding applications of solar energy is limited as they pay very little attention to the issue of solar-energy education. It is a fact that the lack of public awareness about solar energy is one of the obstacles that limits the utilization of an important and freely available energy source that is virtually inexhaustible. At all levels, from school to university education; training programs for professionals, organizing short courses, workshops and seminars dealing with different topics of solar energy; proper campaigns to convince decision makers and industrial leaders of the need for solar-energy technologies; and publication of literature on solar energy technologies in non-technical language for distribution to the general public [12,13].

13.10. Solar power plant (On-Grid, Roof-Top)

A solar power plant of 2 MW_P photovoltaic (PV) capacity was established in 2009 and installed on the roof of one of the University's main academic campus buildings. This plant contains 9300 SunPower high efficiency solar panels, which was considered as the largest PV installation in Saudi Arabia during that date. The photovoltaic plant occupies 11,600 m^2 of roof space and produces 3332 MW hours of clean energy annually, while also saving up to 33,320 t of carbon emissions. The plant output is used to power the campus facilities. The plant biggest challenge was its operation and maintenance (O&M). High amounts of dust and strong winds cause solar panels to become coated with sand very quickly. Thus, two operation teams are scheduled to clean the panels once every 6 day in order to maintain efficiency and output of the system. The project overview data is summarized below:

Installation type: on grid-Rooftop

- **System Size**: 2 MW_P
- **Covered Surface Area**: 11,600 m^2

- **Annual Energy Production**: 3281 MWh
- **Number of PV Panels**(modules): 9300

Mono-crystalline modules

- **Inverters** data: Conergy 280 K central
- inverters
- **Mounting System**: Conergy Suntop III
- mounting Systems
- **SunPower Product**(s): SPR 215 W
- **Project Completion Date**: April 2010

CO_2 Emissions Saved 33,320 t/year
The project benefits are:

- Reduction of 1700 t of carbon emissions annually.
- Raises awareness about the benefits of Alternative energy.

13.10.1. *Other projects on solar energy*

The average solar heating energy produced per square meter of collection area is about 30 kWh. The calculated cost of 1 kWh of useful heating energy from solar is around SR 0.13 $. The largest application of solar energy in Saudi Arabia is the solar-powered heating complex of the King Abdulaziz Airborne Training School in Tabuk. Solar collectors covering a total surface area of 4370 m^2 were used. The collected solar heat is used to supply 40% of building heat and 100% of domestic water needs to serve 400 houses. More than 1100 solar flat-plate collectors have been installed on rooftops of 373 residences of different categories (villas, terraced houses, apartments). Each family residence is equipped with three solar flat-plate collectors 6.36 m^2 total surface area. and a hot water storage tank of 65 gal capacity. The total effective surface area of the solar flat-plate collectors on the KACST campus is 2249 m^2, which generates about [illegible] of useful heating energy.

13.11. *New approach*

A new approach to RO membrane and thermal MSF processes was developed by the Saline Water Conversion Corporation (SWCC). This is called tri-hybrid, NF-SWRO-MSF arrangement. In this process, NF pretreatment unit, which received filtered seawater feed (coagulated with 0.4 mg/L Fe^{3+}) was placed ahead of a seawater reverse osmosis (SWRO) or a multistage flash (MSF) pilot plant to form, a fully integrated pilot plant system of an NF-SWRO or NF-MSF and tri-hybrid of NF-SWRO-MSF system, as shown in Fig. 43 [25].

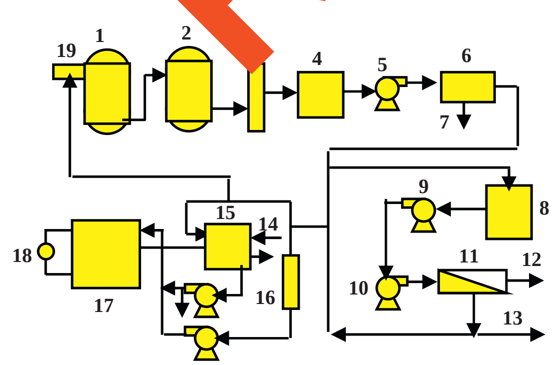


Fig. 43. Schematic flow diagram of NF, SWRO and MSF pilot plant [25]. 1: Coarse filter, 2: fine sand filter, 3: cartridge filter, 4: tank, 5: pump, 6: nano filtration unit(NF), 7: NF reject, 8: tank, 9: booster pump, 10: high pressure pump, 11: RO membrane, 12: product water, 13: reject to MSF unit, 14: sea water inlet, 17: 4-stages MSF unit, 18: brine heater, 19: sea water intake.

Utilizing this process at the pilot plant levels, SWCC RDC demonstrated that the NF pretreatment of seawater feed to desalination plants gives the following benefits:

(1) Prevented SWRO membrane fouling by the
(2) removal of turbidity and bacteria.
(3) Prevented scaling (both in SWRO and MSF) by removal of scale forming hardness ions, (e.g., SO4$^-$ by up to 98%, and total hardness by up to 93%) and
(4) Lowered the required pressure to operate SWRO plant by reducing seawater feed TDS by 30:60%, depending on the type of NF membrane and operating conditions. The net effect of this NF pretreatment was an increase of 50 to 100% in SWRO potable water yield by increasing percent recovery from 35 without NF pretreatment to 50-70 with NF feed pretreatment. NF pretreatment is expected to lower water cost by about 30%.

Finally it was concluded that, use of NF as pretreatment for both RO and MSF processes enhances the production of desalted water by more than 60% and reduces the cost by about 30% [25].

14. Economic analysis

14.1. *Key cost data*

In addition to the technical key data discussed above, the main cost figures have to be assessed as well. Generally the costs are divided into two main categories, namely the capital expenditures (CAPEX) and the operational expenditures (OPEX). Specific CAPEX ranges that have been observed since the late 1990s are summarized in Table 16.

The OPEX can substantially vary depending on the project specifications. The itemized OPEX data of the various desalination technologies are presented in Fig. 44.

From (Fig. 44), it is clear that SWRO technology features is the most economical OPEX (0.47 US\$/m^3). The distance to MED (0.54 US\$/m^3) is significant, but not immense. In consequence, it is quite realistic to assume that the MED technology is competitive with the SWRO technology under special circumstances. Compared

Table 16
Specific CAPEX ranges for different desalination processes [6].

Specific CAPEX \$/(m^3/day)			
Period	**MSF**	**MED-TVC**	**SWRO**
1998–2005	900–1750	900–1450	650–900
2006–2008	1700–2900	1700–2700	1300–2500

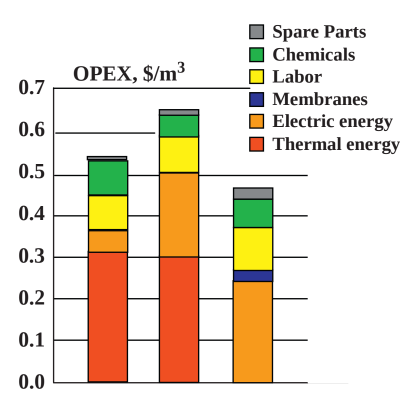


Fig. 44. OPEX for conventional desalination technologies(GWI 2010) [6].

to this, the substantially higher OPEX of the MSF technology (0.65 US\$/m^3), has to be considered to be quite prohibitive.

For different two locations, the OPEX costs are estimated and plotted for MED and RO technologies in Figs. 45 and 46 for MED, Figs. 47 and 48 for RO respectively [6]. It is clear that for the same technology, the OPEX distribution is little bet dependant on the plant location. Also, the costs for energy consumption represent a greater share relative to overall operational expenses for both of MED and RO technologies.

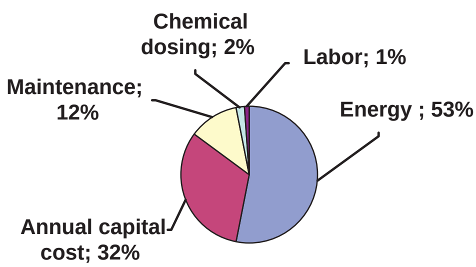


Fig. 45. Summary and distribution of annual CAPEX and OPEX costs for the MED plant located in the Mediterranean sea & Atlantic Ocean for the case DNI:2400 KWh/m^2/yr at coast and fuel type: NG [6].

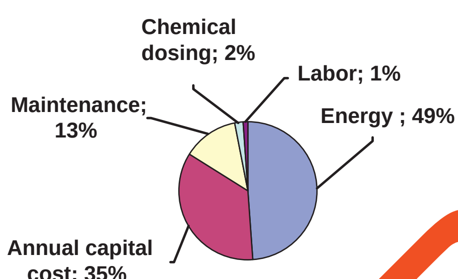


Fig. 46. Summary and distribution of annual CAPEX and OPEX costs for the MED plant located in the Arabian gulf for the case DNI:2400 KWh/m^2/yr at coast and fuel: NG [6].

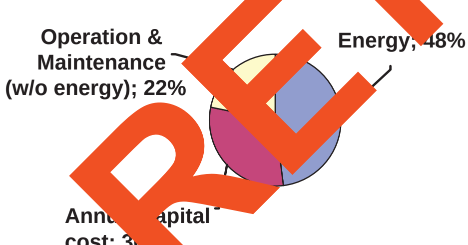


Fig. 47. Summary and distribution of annual CAPEX and OPEX costs for the SWRO plant located in the Mediterranean sea & Atlantic Ocean for the case DNI:2400 KWh/m^2/yr at coast and fuel: NG [6].

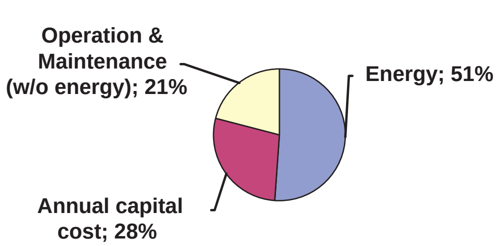


Fig. 48. Summary and distribution of annual CAPEX and OPEX costs for the SWRO plant located in the Arabian gulf for the case DNI:2400 KWh/m^2/yr at coast and fuel: NG [6].

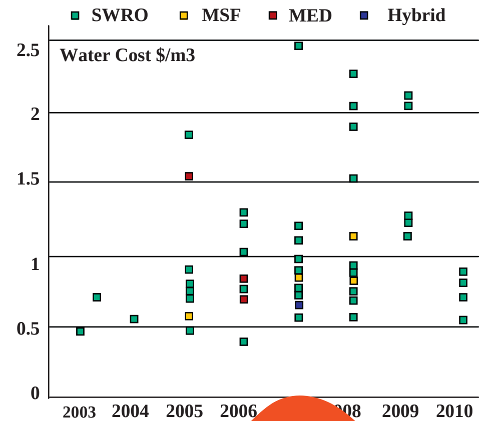


Fig. 49. Range of levelized water production costs (\$/m^3) by SWRO plants for different regions, DNI classes and fuel options including pre-treatment options [6].

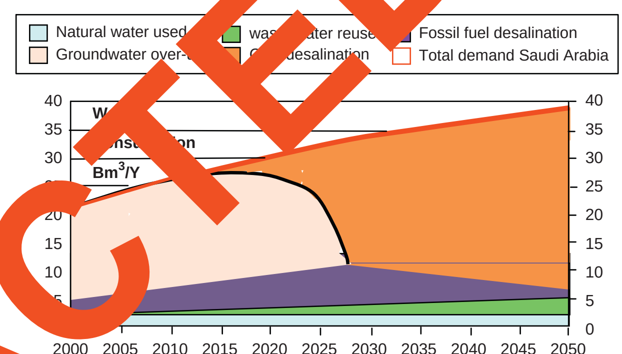


Fig. 50. Water demand scenario for KSA until 2050 and coverage of demand by sustainable sources, by unsustainable sources and by solar desalination [6].

14.2. *Levelized Water Costs (LWC) of typical desalination plants*

The LWC of an item consists of the total cost of procurement and operating this item over its lifetime (CAPEX & OPEX). Range of levelized water production costs (\$/m^3) from different desalination plants since 2003 are represented in Fig. 49. It can be noticed that the cost values per m^3 varies between 0.5 and 2.5 \$/m^3.

15. Desalination projects outlook and strategic direction for KSA [5,6]

Considering the fact that Power and desalination plants consume more than 1.5 million barrels of oil per day. In the other hand, the environmental impact of the new desalination capacities must be as low as possible. To achieve this, it is essential for the region to use Solar Energy instead of fossil energies.

The market potential of solar powered seawater desalination between the year 2000 and 2050 is shown in Fig. 50.

Fig. 50 shows that considerable amounts of water desalted by renewable energy cannot be achieved in the short term. This is because renewable energy production still has to be built and related investments must be achieved. Until 2020, the scenario assumes a rather quick expansion of CSP for desalination. However, it also shows that it will easily take 8–13 years from now until the CSP shares will attain a noticeable weight in the MENA region.

16. Conclusions

Water supply in Saudi Arabia relies heavily on desalination. Saudi Arabia has the largest desalination market in the world.

In KSA the average annual direct normal irradiance (DNI) above 6 kWh/m^2/day which are preferred for CSP operation. So, the present study was directed to study the future sustainable technologies for KSA, looking for more efficient future desalination systems. It is concluded that:

- Different desalination technologies available and applied worldwide were discussed. Some of them are fully developed and applied on a large scale, while others are still used in small units for demonstration purposes or for research and development.
- Comparing MSF and MED, it becomes clear that MED is more efficient in terms of primary energy and electricity consumption and has a lower cost. Moreover, the operating temperature of MED is lower, thus requiring steam at lower pressure Thus, the combination of CSP with MED will be more effective than a combination of CSP and MSF desalination. Thermal vapor compression is often used to increase the efficiency of an MED process, but it requires steam at higher pressure if connected to a steam power plant.
- Comparing the mechanical driven desalination options, reverse osmosis has a lower electricity consumption and cost per unit product water than the mechanical vapor compression method.
- The low performance characteristics of MSF and MVC have lead to the selection of MED and RO as reference technologies for future.
- The much lower primary energy consumption of RO and the slightly lower cost compared to MED suggests that RO might be the preferred desalination technology anyway. However, if MED is coupled to a power plant, it replaces the cost of the condensation unit of the steam plant and partially uses waste heat from power generation for the desalination process. In this case, not all the primary energy used must be accounted for the desalination process, but only the portion that is equivalent to a reduction of the amount of electricity generated in the plant when compared to conventional cooling at lower temperature, and of course the direct power consumption of the MED process.
- Processes combining thermal and mechanical desalination may lead to more efficient future desalination systems.
- hybrid desalination plants were discussed: [illegible] MSF-RO, Nano-filtration–MSF and Nuclear- powered-MSF-RO. The hybrid desalination systems are proven to be technically feasible, economically attractive, and environmentally favorable.
- Hybridization of SWRO and [illegible] technology was considered to improve the performance of latter and reduce the cost of the produced water.
- For hybrid RO-M[illegible] using option of nuclear desalination, the experience has [illegible] operation of such plants for providing water for domestic as well as industrial needs.
- The maturity of point concentrating systems is not as high as that of line concentrating systems. Up to now, line concentrating systems have had clear advantages due to lower cost, less material demand, simpler construction and higher efficiency, and there is still no evidence of a future change of that paradigm. On the other hand, neither parabolic troughs nor linear Fresnel systems can be used to power gas turbines. In this case of high-temperature range up to 1000 °C and more, central receivers are the only available option to provide solar heat for gas turbines and combined cycle systems. However, it is still uncertain whether the technical challenge involved with such systems will be solved satisfactorily, and if large scale units will be commercially available in the medium term future. The early stage of development of those systems still leaves open questions with respect to cost, reliability and scalability for mass production at large scale, although their feasibility has been successfully demonstrated.
- Environmental Impacts of Desalination plants were discussed in details. The proposed Options for environmentally enhanced cases are:
- Enhanced CSP/MED plant
- Enhanced CSP/RO Plant
- Also selection guide of Reference Plant Configuration was given.
- Existing applications of Solar energy-desalination plants, in KSA has been analyzed, to include lessons learned to be reference for future projects.
- Economic analysis has been given, to define the key cost data for different desalination plants.
- Desalination projects outlook and Strategic Direction for KSA has been mentioned. The market potential of solar powered seawater desalination between the year 2000 and 2050 was plotted
- Environmental issues associated with brine concentrate disposal, energy consumption and associated greenhouse gas production were analyzed in details with recommendations for future plants having minimum impact.

Appendix A

A1. Guide for Selection of Reference Plant Configuration

The following [illegible] selection guide for the different options including advantages, disadvantages and energy storage method for each option as given below:

Option-1: Central Receiver with Combined Cycle
High temperature fluid (HTF) Options: compressed air
Advantages: high efficiency for electricity, can be placed in difficult terrain.
Disadvantages: not yet demonstrated, Storage: not yet available but possible (ceramics)

Option-2: Central Receiver with Gas Turbine
HTF Options: compressed air
Advantages: can be placed in difficult terrain, no water consumption of power block and low cost power block.
Disadvantages: reject heat at very high temperature for MED, low efficiency for electricity, high space requirement, only prototypes are available.
Storage: not yet available but possible (ceramics)

Option-3: Central Receiver with Steam Turbine
HTF Options: molten salt, direct steam, air
Advantages: can be placed in difficult terrain
Disadvantages: steam is more expensive than by linear concentrators, high space requirement and only prototypes available
Storage: molten salt and ceramics demonstrated

Option-4: Linear Fresnel with Steam Turbine
HTF Options: direct steam (oil or molten salt possible)
Advantages: low cost collector, low space requirement, easy integration (buildings, agriculture)
Disadvantages: only prototypes are available
Storage: phase change or molten salt

Option-5: Linear Fresnel for Direct Heat
HTF Options: direct steam
Advantages: low space requirement easy integration (buildings, agriculture)
Disadvantages: only prototypes available
Storage: very easy (hot water)

Option-6: Parabolic Trough with Steam Turbine
HTF Options: oil, direct steam, molten salt
Advantages: most mature technology large plants build in Spain and USA (Acciona, Cobra)

Disadvantages: high precision required high cost high land requirement no easy integration to buildings or agriculture
Storage: concrete, phase change or molten salt.
Advantages: direct steam generation, low temperature collector is available
Disadvantages: high cost
Storage: very easy (hot water)

See Figs. A1–A7.

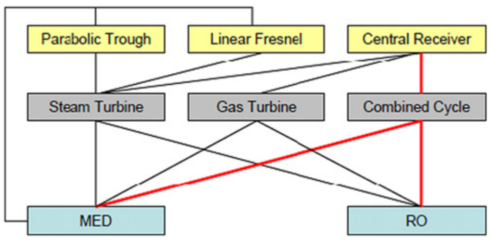


Fig. A1. Central Receiver with Combined Cycle.

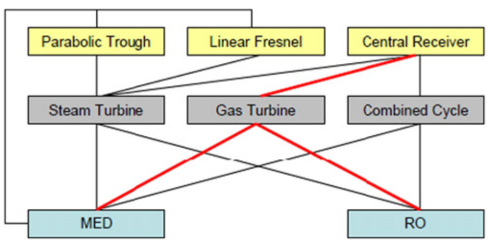


Fig. A2. Central Receiver with Gas Turbine.

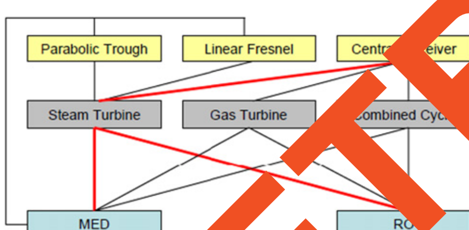


Fig. A3. Central Receiver with Steam Turbine.

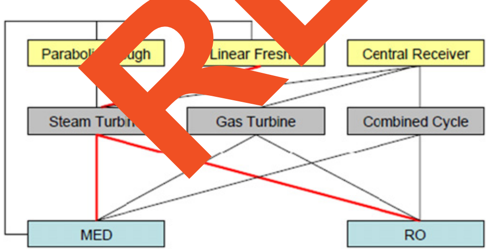


Fig. A4. Linear Fresnel with Steam Turbine.

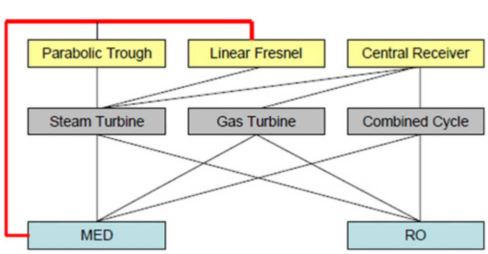


Fig. A5. Linear Fresnel for direct heat.

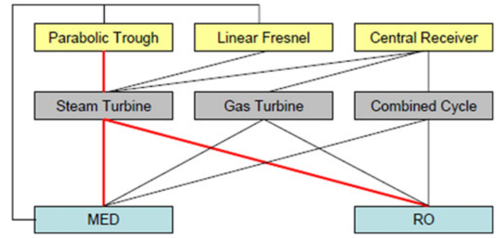


Fig. A6. Parabolic Trough with Steam Cycle.

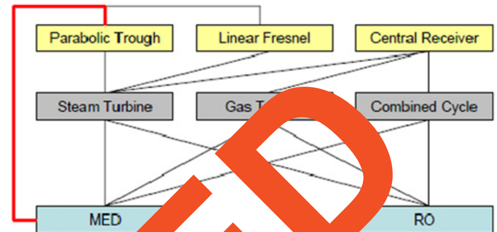


Fig. A7. Parabolic Trough for Direct Heat.

A2. List of projects conducted in KSA [13–31]

See Tables A1 and A2.

A3. Current projects in KSA [6]

The Current Desalination Projects are itemized below:-

- Saudi Arabia Al Khafji: 5680 m^3/d, at design stage
- Saudi Arabia Al Khafji solar-powered SWRO 20,000–50,000 m^3/d SWRO Early stage of procurement
- Saudi Arabia Al Khobar 2 expansion,Tender process ongoing
- Saudi Arabia Al-Waji 4 11,000 m^3/d–13,500 m^3/d, MED, Re-tender delayed
- Saudi Arabia Duba phase 4: 9000 m^3/d, MED Re-tender delayed
- Saudi Arabia Gasan industrial RO plant 83,000 m^3/d RO, Early conceptual stage
- Saudi Arabia Haql phase 3: 9000 m^3/d, MED Re-tender delayed
- Saudi Arabia Jizan Economic City: 12,000 m^3/d & 3000 m^3/d Technical bids under evaluation
- Saudi Arabia Jubail RO upgrade:78,182 m^3/d, RO Tender process ongoing
- Saudi Arabia Khobar 4 IWPP: 250,000 m^3/d & 250 MW Future plant planned over the next 5–7 years
- Saudi Arabia King Abdullah Economic City 70,000 m^3/d, SWRO Decision on project's future due soon.
- Saudi Arabia Ras Tanura Approx: 150,000m3/d, 1000 MW, Awaiting RFP
- Saudi Arabia Shoaiba 4 IWPP: 650,000 m^3/d & 665 MW Future plant planned over the next 5-7 years
- Saudi Arabia Shuqaiq 3 IWPP: 175,000 m^3/d, MSF Awaiting RFP
- Saudi Arabia Yanbu:6000 m^3/d, EPC bids under review
- Saudi Arabia Yanbu 3: 550,000 m^3/d & 1700 MW, Bids submitted

A4. Major players in water desalination [6]

- Austria, Aqua Engineering GmbH, www.aqua-eng.com – *owned by Christ Water Technology Group*
- Cayman Islands, Consolidated Water, www.cwco.com
- France, Suez Environnement, www.suez-environnement.com
- France, Veolia Water Solutions & Technologies, www.veoliawaterst.com/en/

Table A1
List of desalination plants conducted in KSA.

Location	Process type	Capacity M^3/day	Electricity MW	Year of operation	Expected remaining life yrs	No. of units
West coast						
Jeddah ph2	MSF	37,916	71	78	0	4
Jeddah ph3	MSF	75,987	200	79	0	4
Jeddah ph4	MSF	190,555	500	81	1	10
Jeddah ph1	RO	48,848	–	89	9	10
Jeddah ph2	RO	48,848	–	94	14	10
Yanbu ph.1	MSF	94,625	250	81	1	5
Yanbu ph.2	MSF	120,096	35	99	19	4
Yanbu RO	RO	105,904		99	19	15
Shoaiba ph.1	MSF	191,780	157	89	9	10
Shoaiba ph.2	FSF	390,909	340	2002	21	10
Shuqaiq ph1	MSF	83,432	62	89	9	4
Hagl Ph.2	RO	3784		90	10	2
Duba Ph3	RO	3784		89	9	2
Alwajh ph2	MSF	473		79	0	1
Alwajh transferred ph1	MED	825		81	1	2
Alwajh transferred ph2	MED	1032		83	3	4
Alwajh transferred ph3	MSF	473		79	[illegible]	1
Alwajh ph3	MED	9000		2009	[illegible]	-
Umm lujj ph2	RO	3784		86	6	1
Umm lujj ph3	MED	9000		2009	[illegible]	-
Rabigh ph.1	MSF	1204		82	[illegible]	2
Rabigh transferred ph.1	MSF	774		79	0	1
Rabigh transferred ph.2	MED	18,000		2009	–	-
Al aziz Ph.1	MED	3870		87	7	3
Al Birk ph.1	RO	1952		83	6	1
Farasan ph.1	MSF	430		[illegible]	[illegible]	1
Farasan transferred ph.1	MED	1075		78	0	5
Al-Qunfida ph.1	MED	9000		–	–	–
Total		1,458,360	1615	–		112
East Coast						
Location	Process type	Capacity M^3/day	Electricity MW	Year of operation	Expected remaining life yrs	No. of units
Jubil ph.1	MSF	118,447	238	[illegible]	4	6
Jubil ph.2	MSF	815,185	762	83	5	40
Jubil RO	RO	78,182	[illegible]	2002	19	15
Al-Khobar Ph.2	MSF	191,780	[illegible]0	82	4	10
Al-Khobar Ph.3	MSF	240,800	[illegible]1	2002	24	8
Khafji Ph.2	MSF	19,682	[illegible]	85	8	2
		1,464,[illegible]	1811			81

Marafiq's water production facilities

Plant name	Process	M^3/day	Power	Installed date
Jubil #1	MS[illegible]	16,000		84
Jubil#2	[illegible]	32,000		96
Jubil WPP	[illegible]ED	800,000	2500	–
Yanbu MSF1	MSF	27,300		82
Yanbu MSF2	M[illegible]	54,510		86
Yanbu MSF3	[illegible]	27,400		96
Yanbu RO	SW[illegible]	50,400		2007

Table A2
List of solar energy projects conducted by the ERI, KACST, KSA [39].

Projects	Location	Duration	Applications
350 kW PV system (2155 MWh)	Solar Village	1981–87	AC/DC electricity for remote areas
350 kW PV hydrogen production	Solar Village	1987–93	Demonstration plant for solar plant (1.6 MWh) hydrogen production
Solar cooling	Saudi universities	1981–87	Developing of solar cooling laboratory
1 kW solar hydrogen generator (20–30 kWh)	Solar Village	1989–93	Hydrogen production, testing and measurement (laboratory scale)
2 kW solar hydrogen (50 kWh)	KAU, Jeddah	1986–91	Testing of different electrode materials for solar hydrogen plant
3 kW PV test system	Solar Village	1987–90	Demonstration of climatic effects
4 kW PV system	Southern regions of Saudi Arabia	1996	AC/DC electricity for remote areas
6 kW PV system Solar seawater desalination	Solar Village	1996–98	PV grid connection
PV water desalination (0.6 m3 per hour)	Sadous Village	1994–99	PV/RO interface
Solar-thermal desalination	Solar Village	1996-97	Solar distillation of brackish water
PV in agriculture (4 kWp)	Muzahmia	1996	AC/DC grid connected
Long-term performance of PV (3 kW)	Solar Village	Since 1990	Performance evaluation

Table A2 (*continued*)

Projects	Location	Duration	Applications
Fuel cell development (100–1000) W	**Solar Village**	**1993-2000**	**Hydrogen utilization**
Internal combustion engine (ICE)	**Solar Village**	**1993–95**	**Hydrogen utilization**
Solar radiation measurement	**12 stations**	**1994–2000**	**Saudi solar atlas**
Wind energy measurement	**5 stations**	**1994–2000**	**Saudi solar atlas**
Solar dryers	**Al-Hassa, Qatif**	**1988–93**	**Food dryers (dates, vegetables, etc.)**
Two solar-thermal dishes (50 kW)	**Solar Village**	**1986–94**	**Advanced solar stirling engine**
Energy management in buildings	**Dammam**	**1988–93**	**Energy conservation**
Solar colletors development	**Solar Village**	**1993–97**	**Domestic, industrial, agricultural**
Solar refrigeration	**Solar Village**	**1999–2000**	**Desert application**

- Spain, Acciona Agua, www.acciona.es
- United States, General Electric (GE), www.ge.com
- United States, Ionics, www.ionics.com – *acquired by GE in 2004*
- United States, Zenon Environmental, www.zenon.com – *acquired by GE in 2006* As part of *Ecomagination* program, General Electric is currently building up a portfolio of companies specialized in water treatment and desalination technologies.

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